Power communications over the last kilometre

Thesis

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Power Communications over the Last Kilometre

by

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Memorandum

All work and ideas recorded in this dissertation are original unless otherwise acknowledged in the text or by reference. The work has not been submitted in support of an application for another degree in this university, nor for any degree or diploma at any other institution.

Contents

Abstract

This thesis examines traditional methods of transmitting and receiving information over the last kilometre into homes and light industrial premises. As a direct result of the deregulation of electricity with the Electrical Deregulation Act of July 1989 [1] and the proliferation of large scale integration electronic devices such as microprocessors the need to transmit more data to and from such premises became urgent.

The last kilometre problem of getting information to and from the customer's premises to the node or data concentrator for connection to the available services, such as the internet, applies to any supplier from those that need to transfer large amounts of date such as on demand high definition television to those wishing to read utility meters remotely.

Two competing techniques for transmitting small amounts of data at low data rates over the last kilometre between domestic and light commercial sites to the utility substation are investigated in this thesis. These techniques are narrow band VHF radio and low frequency power line carrier.

A literature survey investigates the traditional methods of delivery information and the use of home networks and the latest research in power line carrier and broadband power line. The basis of radio propagation is presented including Maxwell's equations.

Two sets of trials are presented; the first set investigates a low frequency power line technology broadcast alarm system designed to inform residents living in higher risks areas around industrial sites such as oil refineries and chemical factories of important information and any alarm condition. The second set of trials, the radio trial, at 184

MHz, involved reading 2,500 domestic and light industrial electricity meters every 30 minutes during two week long periods.

Conclusion

Both the radio meter reading system and low data rate power systems are viable in getting low data rate information to and from domestic and commercial properties. Both systems may be retrofitted quickly and cheaply depending on the data rates and amount of data to be transmitted. The radio meter system benefited from careful site surveys including monitoring of potential radio interference; the power line carrier system also benefited from site surveys and monitoring of line disturbance and line impedance.

Chapter 1 Developments in Communications over the Last Kilometre

1.1 Introduction

The 'last kilometre' problem is where a utility or communications provider is faced with installing a connection of some type to every home, office, commercial site and industrial site that requires that connection or communications link, as shown in figure1.. The Main Data Link between the data concentrator, sited at a suitable location, and the PHY layer of the information / entertainment source (or gateway to World Wide Web), while difficult to install, is a small proportion of the cost of the installation of the links to each site.

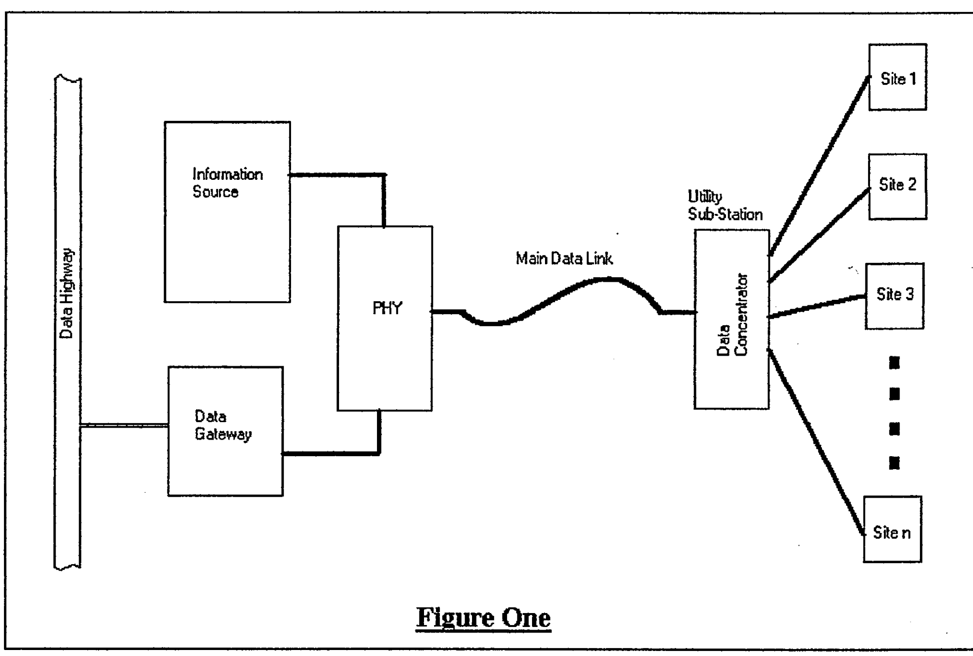


Figure 1 Block Diagram of an Automatic Meter Reading system

This thesis describes the 'last kilometre' problem whose objective is to provide reliable two way communications, of sufficient bandwidth, to every site that requires it. The thesis explores two technologies that do not require a large initial investment in running cables or fibre to each and every domestic and light commercial premises in the United Kingdom. The technologies are those of Power Line Carrier and Radio Transmission, namely narrow band VHF or UHF links. The main part of this thesis describes an experiment conducted on 2000+ sites in a town in North East UK where each property's electricity meter reading was recorded every 30 minutes and then regularly transmitted to the Utilities main office. The research comprised a paper and book study of the history and current state of the art of both technologies and experimental/trials work carried out in association with RAMAR Technology Ltd (Radio Automated Meter Reading) and with Symbol Seeker (Power Line Technology).

How can Utilities retain their customer base in the highly competitive deregulated environment and what do the Utility's customers want?

1.2 What do the Utilities need?

The Utilities as with any business need to make a profit and retain their customers or perhaps retain their customers and make a profit. The Utility must maximise profits by collecting monies owed in a timely fashion, the Utility must also be efficient. Both of these objectives need up to date energy consumption data.

To supply customers efficiently and reliably with electricity, gas, fuel, water or heat the Utility needs to know the consumption of each customer, the state of the distribution system, what reserves are available, the weather trends, and an accurate as possible prediction of future consumption. The more up to date the information the more efficiently the system can be managed. To retain customers the Utility companies must also pass some of the cost savings onto the customer in the form of reduced tariffs. They must ensure the quality of service is of such a high standard that an outage of supply is a rare occurrence and that all correspondence, bills and the like are correct.

For the Utility the longer-term objective is to manage the energy demand. To achieve this necessitates the Utility being able to turn off non-essential loads if possible and thus smooth out the demand, leading to less spinning or stockpiled reserves and reduced overheads. Another way to smooth demand is with 'price control' where periods of high demand have high supply costs to the customer. Domestic consumers will then need accurate and up to the minute, or live, price information plus at the very least a semi-automatic way to 'program' their power consumption.

To maintain the customer base in the de-regulated environment the Utility companies have to offer the customers reliability and value for money. Additionally they may offer other inducements or benefits such as single point of sale for electricity, gas, water and heat, plus billing on demand, cheap telephone calls, internet access or even multi-media and interactive television. Some of these are now available in the market place in the UK and more are promised soon.

1.3 <u>What do the Customers want?</u>

Customers want less expensive bills, a totally reliable supply, a simple way to pay the bills and possibly secondary or value added services such as alarm monitoring, cheap telephone calls or even multi media. Domestic customers are only likely to purchase and install equipment in their homes to take advantage of varying energy costs if the equipment is simple to install and use. It must offer worthwhile savings and some marked improvement over that offered by other suppliers or alternatively if the service or device is in fashion with the public.

Note the infrastructure must be in place to enable the system to work as advertised. Potential customers are quickly lost when rumours of poor operation or reliability get around.

Commercial and industrial customers already have some parts of these value added services available to them and are likely to take up other services as soon as they mature sufficiently to overcome the natural conservatism evident in the UK Utility industry following deregulation.

For any Utility it is the install base of domestic customer utility meters that constitute by far the largest source of data collection opportunities and problems. One of the main obstacles, besides cost, to gathering the information from this install base is the 'last kilometre' from a sub station or other installation to each domestic dwelling or commercial site.

When considering ways to transmit or receive information, in analogue or digital form, over this difficult 'last kilometre' there are many factors that have to be taken into account, for instance the availability of an already installed and suitable communications channel for the type of information to be transmitted. The channel requirements will be quite different for a once per day reading of the water meter with relatively little data content, as for example a telephone conversation.

There is a lot of discussion, many trials and some installation and roll out of various asymmetrical communications channels such as ADSL. The amount of data transmitted from a home as distinct to that transmitted to a home is much less, even for Internet access and other entertainments such as multimedia. An example often used to illustrate this is home shopping over the Internet or cable TV channel, where the data flowing into the home can be photographs or motion pictures of goods including sound and large amounts of text. The output from the home is a simple request to buy those goods or services and some security information. This means that the channel into the home requires a higher bandwidth compared with the reverse direction. With the advent of

Small Office Home Office (SOHO) and other types of home working the channel from the home/office to the data concentrator is increasing all of the time. The bandwidth of a signal is the amount of frequency spectrum that it occupies and is a function of data rate and modulation method.

For the transmission and reception of data over a communications channel there are some significant properties that determine the bandwidth required of that communications channel. These are the amount of data to be sent, the speed at which the data must be transmitted, whether the data is synchronous or asynchronous, and the quality of service. Synchronous or real time data is time sensitive, for example speech where if it is split up and jumbled in time the sense of the conversation will be lost. Large lags in time between transmission and reception will also cause problems and loss of intelligibility. Asynchronous data is not real time and can be delayed; the data tends to be split into sections, or packets, and sent at different times and sometimes even by different routes. The packets can be sent using the most efficient route and even used to 'pack' an alternative communications channel ensuring maximum use of that channel.

The amount of data to be sent and the speed of transmission will govern the bandwidth requirements as described by Shannon [13]. There exist many different modulation methods and techniques that utilise the available bandwidth of the channel with varying efficiencies. This engenders a trade off between the complexity of the modulation technique and the cost of the equipment and between the bandwidth of a channel and the data rate transmitted over that channel. As a general rule the more robust or tolerant of noise and fading that is required the lower the data rate that can be transmitted over a given communications channel. The various links used to cover the last kilometre are discussed further in chapter 2 of this thesis.

The required data rates for various multimedia data streams include

Moving Pictures Experts Group 2 (MPEG2) = 2MBPS to 4MBPS

Digital Video Disc (DVD) = 3MBPS to 8MBPS

High definition Television (HDTV) = 14MBPS

1.4 History of Meter Reading

Utility meters have been installed at the site of supply almost since the centralised supply of electricity started with the Electric Lighting Act of 1888 [2]. Traditionally the utility meter has been read by a meter reader who is a semi skilled professional person. The meter reading was written down and then transferred to a ledger or later a computer for the generation of bills for the customers. With the advent of portable handheld computers the route management and input of meter readings has become semi automated in that the route the meter reader must follow is downloaded in to the hand held computer each day; when the meter reader gains access to a meter to be read he will type the reading into the hand held computer and proceed to the next site as instructed by the route management software. At the end of the day the readings are uploaded to the Utilities billing computer.

There are several problems to be overcome during such an operation, these include difficult entry to the meter site if the site occupants are not at the site when the meter reader needs to gain access, animals or pets that wish to protect their territory or access to the meter due to poor location or the site occupants covering the meter with structures, furniture or goods. Another problem encountered by the Utilities is the difficulty to access the meter due to safety or security issues. Many industrial meters are mounted at sites where access is problematic at best. One example is a water meter under a man hole in a busy city trunk road. Access to this meter involves getting a license to close the road for a period with all of the issues of setting up coned areas, blocking a busy route, safety of the personnel, pumping out of the meter pit, all to read a water meter. A vehicle based radio meter reading system allows the meter to be read while driving passed the site.

Meter reading in the UK is traditionally carried out on each meter on a monthly (commercial) or quarterly (domestic) cycle so as not to disturb the site occupants too often. The deregulation of supply of electricity, water and gas has stepped up competition between the various supply companies and caused the formation of spin offs and companies setup to read utility meters on a contract basis. An Automated Meter Reading (AMR) system to read all types of meter would greatly benefit any company or Utility by reducing the number of meter readers required and thus releasing staff for maintenance or customer relations duties.

The regulatory bodies for the relevant utilities have laid down plans to allow meter reading to take place automatically on a more regular basis. The meter reading may be taken as often as every 30 minutes. This would allow the site occupants to take advantage of the fluctuating cost of the supply and choose when to use that supply; in fact this facility has been available to larger industrial customers for some years. This is the first step towards demand side management which is the holy grail of the utility industries.

Demand side management is where the Utility can reduce demand on the generating station or other resource by switching off some of the less sensitive loads. This would mean that, for example in the electricity industry, spinning reserves, that is generators that are being turned by the prime mover but do not have a load applied to them. Spinning reserves allow for a large demand to be serviced quickly but of course cost money in the form of energy required to keep the generator spinning as well as wear and tear on the equipment. Another option to spinning reserves is to import/buy the resource from another Utility in a different area or even a different country. This is also implemented in the UK but is not as cost effective as demand side management promises to be.

Various meter types are in use in the UK and abroad with electromechanical meters mostly used in electrical metering applications. The majority of installed Gas and Water meters are mechanical in operation although electronic meters are becoming more common. The electromechanical electricity meters are more correctly called watt / hour meters and will maintain their calibration for up to 25 years and then can be refurbished to be used for a further 25 years. These electromechanical meters measure the voltage, current and the phase angle between them. Electronic meters are finding a place in the UK market but usually have only a 10 year recalibration cycle, they are usually more expensive to buy. However the cost continues to fall as the electronic circuits are developed and electronic meters offer much greater functionality and ease of connecting to a metering network. This connection may be wired, capacitive, wireless or optical. The Yorkshire Electricity Group PLC trial was conducted using the Siemens S2AS Electronic meter with an EN 61107 interface which facilitates a simple optical connection to the radio transceiver and is further described in chapter 6 of this thesis.

Both the Gas and water industry utilise mechanical meters to monitor consumption at each customers premises. The Gas meter uses a bellows principle to measure gas consumption which tends to be reasonably safe in all situations. Electronic gas meters are being used more and more in the market place once the safety requirement has been met; these are mostly based on forward and reverse ultrasonic sensors measuring the gas flow. The water industry tend to use mechanical meters as it is difficult to supply electricity to a water meter pit which is often full of water and usually in the street outside of each premises.

1.5 Automated Meter Reading (AMR)

Automated meter reading provides the Utilities with a more reliable and up to date system to read Utility meters accurately and to provide the half hourly readings as called for in the 1988 Government white paper. AMR can be considered to be 3 tiered where the lowest tier is the walk by system. A walk-by system allows the Utility to access meter transponders, usually by radio, at sites that are difficult to access. The rest of the meter reader's route is covered in the conventional manner of gaining access to the meter and typing in the meter reading onto his hand held computer. The utility meter can be upgraded to remote read with minimum disruption when having other work done to the meter.

The second tier is a drive by system, and this is where the concentration of AMR equipped meters is such that a meter reader instead of reading tens or perhaps hundred of meters per day could in a vehicle equipped with the appropriate system read thousands of meter per day. Another reason for a vehicle based system is where the geographical distance between meters is such that a meter reader needs a vehicle to cover the area.

The third and perhaps ultimate tier is a fixed network system. A fixed network relies on fixed data concentrators usually mounted in the utilities sub station or other convenient structure. The AMR equipped meters in the area of the data concentrator all feed their information to the data concentrator to be forwarded at the appropriate time to the Utilities billing computer.

A spin off from the fixed network is a sub metering system; this is usually at a site such as a block of flats that has one Utility meter at the buildings supply point. The owners of the site will often install meters at each occupier's site to ensure fair distribution of the costs.

Such systems are often fitted with AMR enabled meters and the readings gathered and emailed to the site owner / manager for them to write out the bills.

1.6 Research Objectives

The objective of this research aimed to establish the effectiveness of a radio meter reading network in reading customers electricity meters every 30 minutes and to compare and contrast this with the predicted performance and cost of a possible Power Line Carrier (PLC) system. As a result of the deregulation of electricity generation and distribution, which was a direct result of the Government white paper of 1988 [2], there is a requirement on the utilities to gather meter readings every 30 minutes. This allows all customers the same facilities of using electricity and thus buying electricity at the most cost effective time. This also allows the customer to switch between suppliers and given a reliable automated meter reading system to have their meters read every 30 minutes. The customers choosing when to use the supply at its most economical time would tend to flatten out demand and ultimately reduce the requirement for the utility to have stock piled or spinning reserves and thus reduce the costs and increase efficiency.

The key part of the research was conducted as part of a trial in partnership with RAMAR Technology Ltd. in conjunction with Yorkshire Electricity Group PLC. The research was made up of three trial phases; the feasibility or link budget trial, followed by a technology trial and finally the customer trial.

The Power Line Carrier exercise is a mostly paper based design for a theoretical meter reading system based on the recently available ST integrated circuit design (ST7538P) specifically for PLC applications. The performance will be predicted by using results from a Power Line Technology (PLT) trial of a public alarm system design. The topology of the PLC system will be similar to the design shown in figure 1. At the electricity substation each of the phases will be connected to the data concentrator to provide signalling to all electricity meters serviced by that substation. Links from the Gas and water meters to the electricity meter and then back to the data concentrator would be implemented by a low power short range radio link.

1.7 Development of Thesis

Chapter 1 defines the last kilometre problem and two ways to overcome this problem, radio and power line carrier technology. This chapter then goes on to discuss data types, speeds and bandwidth requirements before giving a brief history of meter reading and finally introduces Automated Meter Reading (AMR)

Chapter 2 looks at traditional methods of communication such as radio, telephone and Asymmetric Digital Subscriber Line (ADSL), PLC, other cable systems and then goes into the problem of the last kilometre in more detail and discusses home networks and the changing requirements for home and SOHO communications.

Chapter 3 describes Power Line Technology (PLT) including its advantages and disadvantages and goes on to describe a PLC system to read electricity meters in domestic and light commercial sites.

Chapter 4 looks at radio propagation in general including Maxwell's equations, propagation modes, legal restrictions, system protocols, polar diagrams and link budgets.

Chapter 5 explains the PLC trials and AMR trials conducted for Yorkshire Electricity Group in Goole.

Chapter 6 examines the results of the AMR trial in Goole and compares these results with the predicted results of the PLC design.

1.8 Summary

Chapter 1 introduced the last kilometre problem and two ways to overcome the problem, one is the use of narrow band VHF radio links to each property and the other is to use the existing mains electricity distribution network to deliver a power line carrier signal to each property. The chapter then goes on to discuss data types and speed requirements and the required bandwidths before giving a brief history of meter reading. The chapter then touches briefly on automated meter reading before listing the chapters in this thesis with a brief outline of what each chapter contains. Chapter 2 describes the last kilometre problem in more detail and discusses the traditional methods of overcoming such problems including power line carrier, PSTN, and cable as well as wireless systems. Chapter 2 then goes on to explain home networks.

Chapter 2 Developments in Home Networks

Introduction

The previous chapter introduced the last kilometre problem as well as data types and channel bandwidths. Chapter 1 also introduced utility meter reading and the concept of automated meter reading. This chapter will continue to examine the last kilometre problem and will discuss some of the methods to bridge the gap and will also examine the reason why the last kilometre problem has become such an issue.

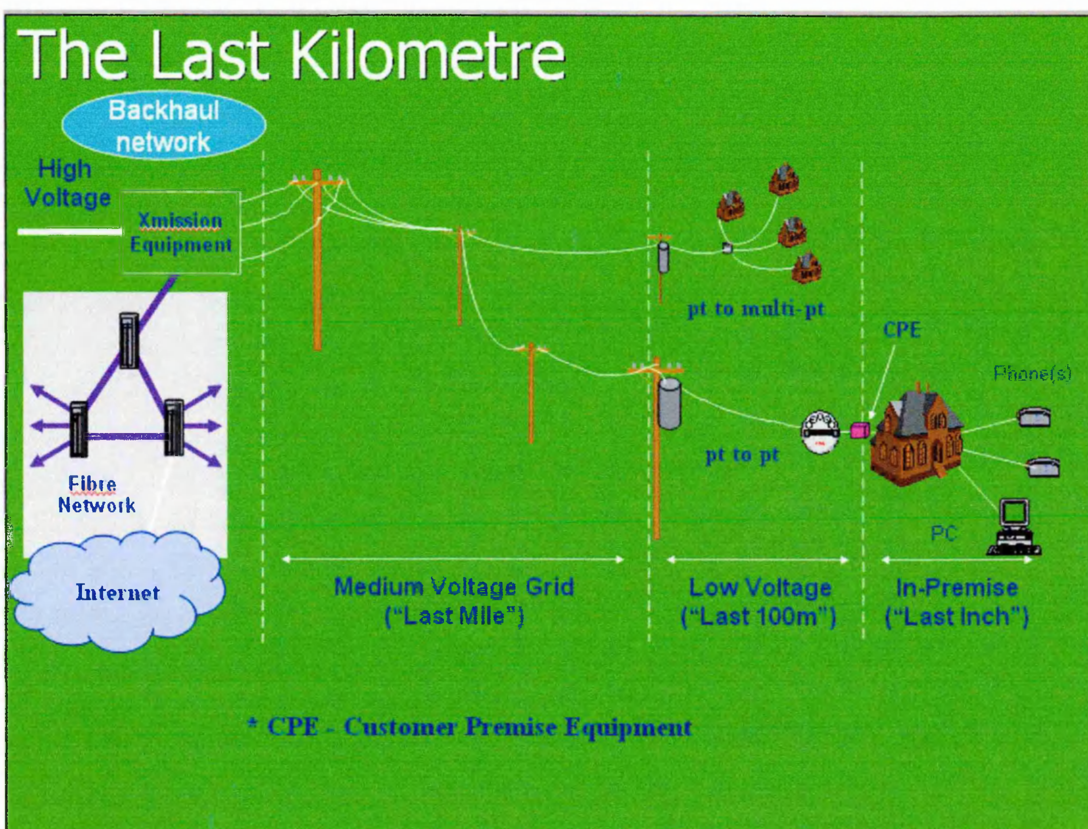


Figure 2 Diagram showing mains connections over the last kilometre [15]

The 'Last Kilometre' to each customer site, as shown in figure 2, presents utilities, entertainment and communications companies with many problems. These include the number of links to be made, the disruption to traffic and other systems in urban environments when installing cables and the distances of those links in rural areas. In densely populated urban areas other problems occur including the high bandwidths that may be required at peak periods due the numbers of customers wanting to use the channel. Cross talk may also become a problem in such dense environments. Another problem may be the high noise levels and other interference encountered in urban and industrial areas. Companies endeavouring to overcome the 'Last-Mile' problem must also contend with non standard interfaces between various equipments and must provide protection and security against eavesdropping, fraud and theft

There are many channels of information over the 'last-kilometre' into a customer site and some of the traditional mechanisms used to transmit the information over that 'last kilometre' are now considered.

2.1.1 Post

The Kings post was started by Henry VIII in 1512 and opened to public use by King Charles 1st in 1635! The speed of this channel can be extremely slow or in the case of lost mail infinitely slow. The main advantage is the amount of information that can be delivered at any one time, for example several films on videotape or many computer programs on CD-ROM. An advantage of this mechanism is that any site anywhere in the world need only have an address recognisable by a local post office to receive the information.

2.1.2 Telephone

The development of the telephone is commonly attributed to Alexander Graham Bell who at the age of 29 patented the telephone just hours before Elisha Gray. The first call made by Alexander Graham Bell was to his assistant in the next room on 10th March 1876. The Public Switched Telephone network (PSTN), as shown in figure 3, grew out of the need for homes and businesses to be connected to a telephone network, which has lead to upwards of 28 million customers in the UK. The bandwidth of the unshielded twisted copper pair (UTP) was limited to about 300Hz to 3.4 kHz. This limited the information carried on this medium; traditionally to voice and slow digital data. Advances in modem design have pushed the data rate up to 64kbit/s, transmitted in the form of tones generated in the modem and received and decoded in a modem at the receiving end. The PSTN networks cover the last kilometre to most sites in the developed world.

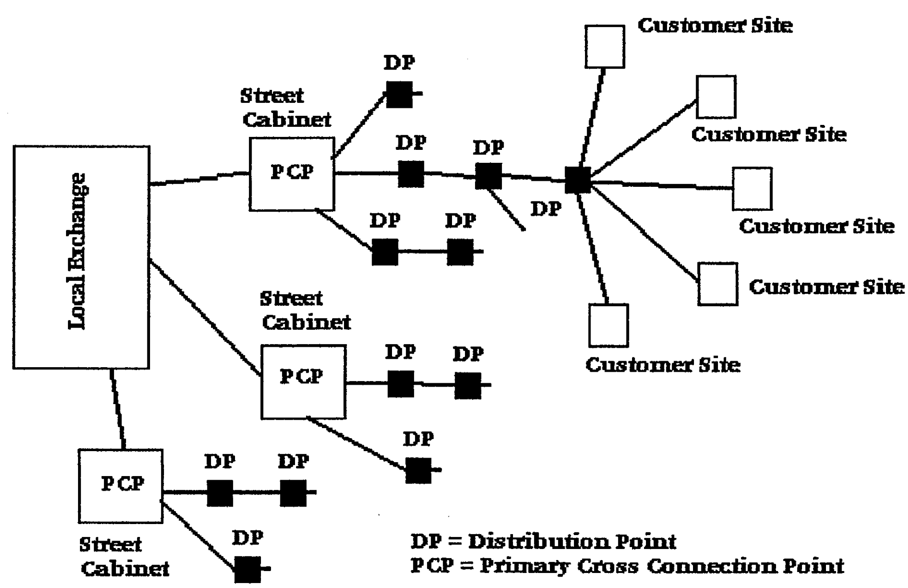


Figure 3 Last Kilometre of the PSTN Telephone Network

2.1.3 Integrated Services Digital Network / Asymmetric Digital Subscriber Line

The initial need for data communications between business sites prompted the development of a system using the existing telephone lines to transmit high data rate information. This became possible when the PSTN networks changed over from purely analogue systems to packet based digital switching networks. The first commercial development was Integrated Services Digital Network (ISDN) which grew out of the International Telephone and Telegraph Consultative Committee (CCITT) Recommendation I.120 (1984). The CCITT was replaced by the United Nations International Telecommunications Union (ITU). The ISDN system transmits data at 160kbits/s over 2 or 3 twisted pairs. Demand for higher data rates increases all of the time so the development of systems using sophisticated modulation schemes to provide data rates between 56kbits/sec to 10Mbits/sec or more is being conducted, still based around the UTP of the PSTN network. The next system was High bit rate Digital /Subscriber Line (HDSL) and then Asymmetric Digital Subscriber Line (ADSL) where the data rate from the local exchange is up to 2Mbits/s and from the customer site to the local exchange is up to 256kbits/s. These high data rate systems, given the generic name xDSL, are targeted primarily at commercial and industrial customers, as they require one or more leased telephone lines dedicated for this usage and the fitting of special equipment at both ends of the telephone line. These systems are shown in Figure 4 and the input power required shown in figure 5. These systems were initially aimed at the commercial sector but have been marketed as an always on broadband link to many homes.

xDSL varieties

Technology	Deployment	Frequency	POTS Splitter	Cable
ADSL	FTTEx	25 kHz - 1.1 MHz	Yes	single pair
ADSL Lite	FTTEx	25 kHz - 552 MHz	No	single pair
VDSL	FTTCab	0.3 - 30 MHz	Yes?	single pair
SDSL	FTTEx	DC - 784 kHz	No	multi pair
HDSL	FTTEx	DC - 784 kHz	No	Multi pair & single pair

FTTEx = Fibre to the exchange. FTTCab = Fibre to the cabinet.

Figure 4 xDSL Varieties [15]

Input Power for xDSL

	ADSL		VDSL (FTTCab)	
	Downstream	Upstream	Downstream	Upstream
Frequency (MHz)	0.138 - 1.104	0.138 - 0.276	1.104 - 10.0	1.104 - 10.0
PSD (dBm/Hz)	- 36.5	- 34.5	- 60	- 60
Power in 10 kHz (mW)	2.2	3.5	0.01	0.01

Figure 5 Input Power for xDSL [15]

2.1.4 Cable TV

Cable TV (CATV) networks which started as Community Antenna Television by John Watson in Pennsylvania in 1948 are now well established in the USA and Canada and are becoming well established in Europe while the rest of the world is slowly being installed with fibre optic or fibre / co-axial cable hybrid television delivery systems. These systems were initially single direction channels, to the home, but are now becoming full two-way 100 MHz bandwidth Bi-directional links. For example in Seattle there is a trial of a two-way cable TV system for 26,000 customers of AT&T that provides a data link 100 times faster than conventional telecom modem. As more features are added to these enhanced cable services this will entice further subscribers bringing in more revenue and allowing further investment in units such as 'Home Gateways'.

2.1.5 Power line carrier

Signalling over the power distribution system, started in the 1920's, was primarily over the 11kv high voltage distribution system. Two main types were implemented, cyclocontrol and ripple control. Both systems are still in use and require very high power transmitters and give low data rates in the order of 10's of bits per second, which are used to control the network. Since that time there have been many trials and installations of low data rate transmission systems where two frequency bands are allocated, 3 kHz - 148.5 kHz in Europe and 50 - 455 kHz in the USA. There are also trials of high data rate power line carrier systems called Broad Band Power Line (BPL) and a high frequency European standard is being developed for the frequency band 1 - 30MHz. Several committees within the European Union, for example CENELEC Technical Committee S/C205A, are looking at the various aspects of power line carrier and the uses to which it can be put. The committees have tended to concentrate on the lower frequency bands and low data rate signals such as meter reading and status and switching signals up until recently but are now concentrating on writing specifications for the high frequency power line carrier system BPL.

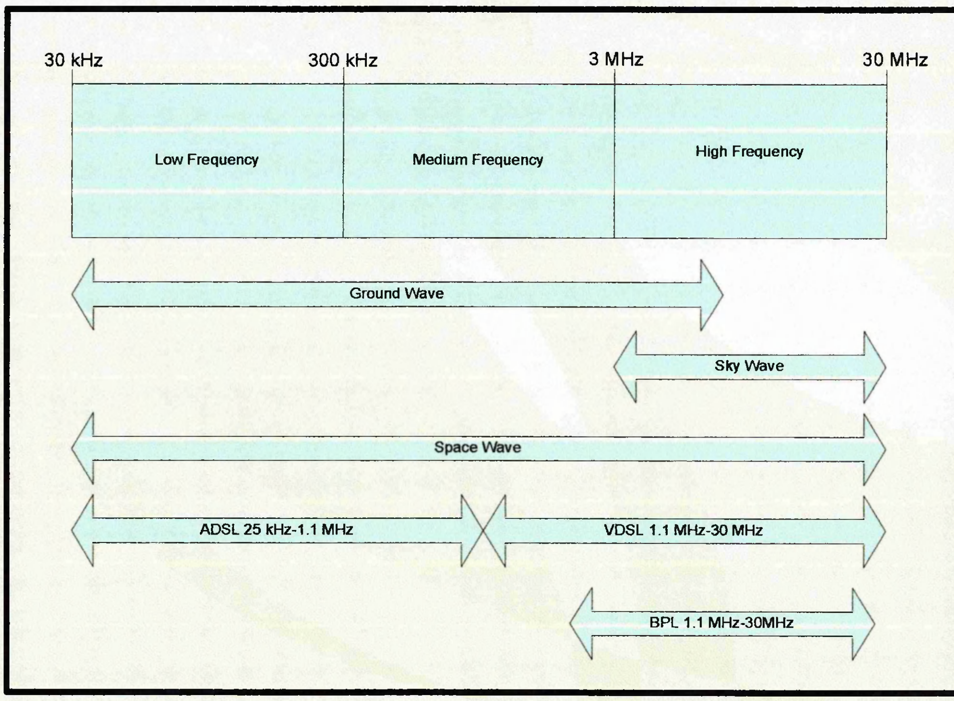


Figure 6 Frequency spectrum used by power line carrier

The advantages of Power Line Carrier are that it already goes the last kilometre to the home. It is distributed to the vast majority of homes and always gathers to a local distribution point owned by the Electricity Distribution Company. The disadvantages are the channel tends to be electrically noisy and prone to EMC radiation, cross talk between adjacent houses, low line impedance and of limited bandwidth BPL is also centred on a part of the spectrum heavily occupied by other users as shown in figure 6.

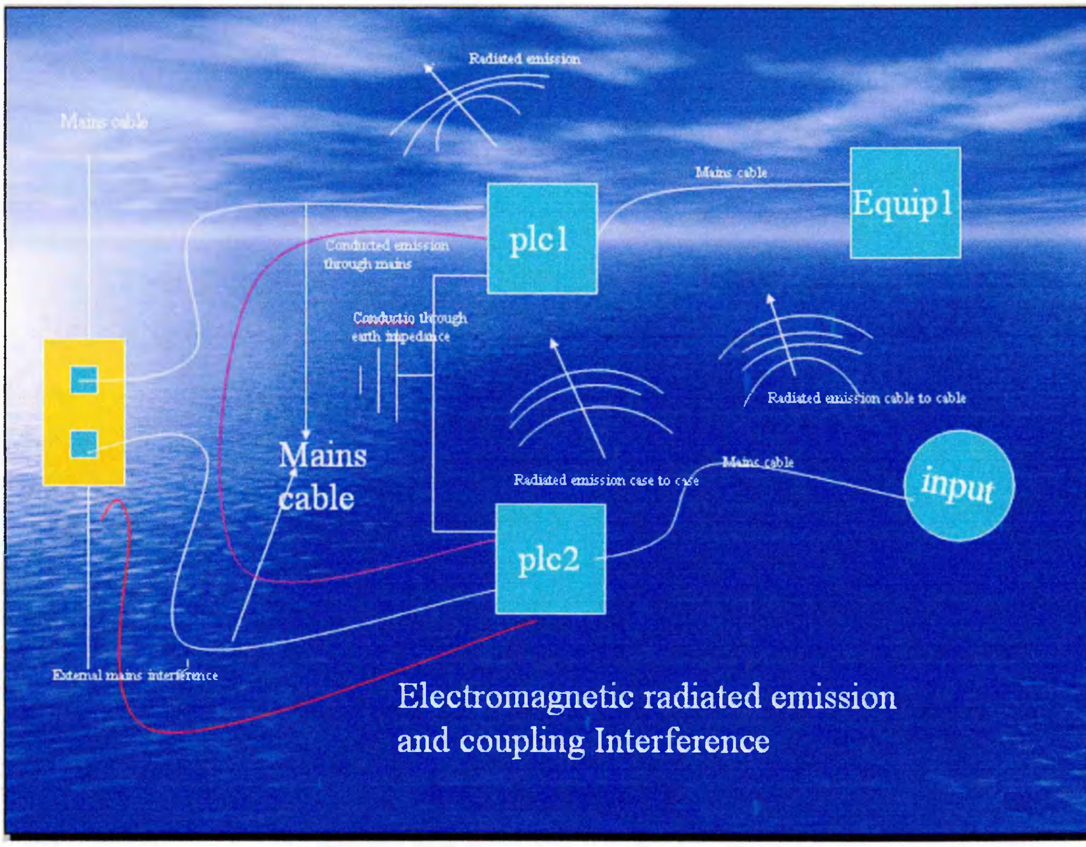


Figure 7 Interference Sources [14]

There are concerns over the higher data rate systems that may suffer from EMC problems as shown in figure 7. The high frequency data signals radiate from the power lines and structures such as streetlights into the environment and cause interference to other established communication channels such as HF radio and long and short wave radio broadcasting. The potential EMC problems have yet to be resolved to the satisfaction of all interested parties but work is being conducted into characterising the potential interference and reducing it to an acceptable level.

2.1.6 Wireless

Wireless impacts on all areas of communications whether directly for example an FM radio transmission or hidden / indirectly for example in terrestrial telephone links where transmission via satellite is often used. Information modulated onto radio carrier waves can be either digital or analogue. With the advent of highly integrated digital circuits in radio systems, digital modulation systems are rapidly expanding and taking over many traditional analogue systems such as telephone and terrestrial radio broadcast.

Radio is tending to be split into three main groups, wide band, broadband and narrow band. Broadband radio is used to carry large amounts of data or information and is mostly confined to the RF frequencies above 1-2GHz. Narrow band radio consists of traditional applications such as private mobile radio and long-range radio links and new specialist applications. Due to the nature of the data and radio link between customer site and sub station meter reading systems tend to be narrow.

Advantages of using a radio link are that the radio link goes to almost all homes within range of the transmitter, the installation costs tend to be lower than other systems with perhaps the power line carrier being the exception. The radio link can be tailored to exact needs of client and is flexible in use.

Disadvantages are susceptibility to interference and jamming, radio links are not secure without some sophisticated encryption applied to the data. The licence requirements on some frequency bands are such that a fee is payable every year and that without careful planning and some redundancy the coverage may vary from one minute to the next. Some sites well within a cell may not be covered.

This phenomenon is due to the way the radio waves propagate around the area or cell covered by the node or data concentrator.

2.1.7 Hybrid Cable Systems

Hybrid cable design offers 622Mbits/second for less than $100 per month [3]; an American company Khasmin Technologies Inc. has launched a cable system that is made up of wire and several single mode fibre optic cables. Initially the wire part only will be used to transmit video, data and voice information. As the costs of the fibre optic interfaces falls more data will be transmitted by fibre optics. This will aid the transition to fibre optics as no added installation costs will be incurred. The availability of high data rate connections will establish a demand for high bandwidth and eventually drive down the costs of fibre optic interfaces.

2.2 Home Networks and Gateways

As Personal Computers (PC's) and Laptop Computers become faster, cheaper and more widely available and with the advent of more people working from home the requirement to link these computers and laptops to each other and to various peripherals becomes ever greater. Many homes in the developed world have more than one PC in the home but there is usually little requirement in the home to have more than one Printer, Document Scanner or Broadband internet connection and this is where a Home Data Network comes into play. Note that a Broad band or 'always-on' connection encourages casual internet use as there is usually no waiting for the connection to be made. There often are some limits on download to limit the data rates required by the back haul link while maintaining a standard of service to all users. Prime home internet usage tends to be between 1800 hours and midnight local time.

Another type of home network is where the home is controlled or automated with the use of a computer, such control includes energy saving functions such as turning on and off lights as rooms are occupied or not, to adjust and maintain the temperature in various rooms, to monitor and report on fires, unauthorized entries and other emergencies. This is the Home Control Network.

A further use of a home network is the home entertainment network where multimedia can be sourced and then routed to the required room as required. Such multimedia content may include films, radio programs, music or games. This is the Home Entertainment Network.

All of these networks require network channels to link the various source or output devices to each other in any and all rooms that require it. This network may use existing channels such as telephone or mains wiring or may require new wiring such as category 5 cabling or fibre optic cabling or may use wireless links. Each of these communication mediums has advantages and disadvantages. Several companies marketing network solutions using telephone, mains wiring or wireless are using the slogan 'No New Wires' to emphasize the cost and disruption of adding new cabling to a home.

All networks have to manage the requirements made by the various units connected to that network especially where two or more units are trying to access the same resource. Thus it is not just a simple job to connect a wire or other communications channel to two units and expect them to work together. Efforts are being made to ease the setup requirements of a network, that is to make them self configuring and self healing but until home networks standards can be agreed that is a far off goal.

One solution may be the Home Gateway where a dedicated unit manages all off the inputs and outputs around the home as shown in figure 8. The home Gateway acts as a PC server linking two or more PCs in any room in the house to all other PCs and peripherals such as printers and document scanners. The Gateway provides firewall facilities to the internet to reduce or prevent unauthorized access or infection by viruses. In addition the Gateway acts as an interface with the cable TV company input routeing various off air, recorded and live stream radio and television programs to most rooms in the house. The Gateway also allows portable digital telephones to connect to the PSTN telephone system and could allow additional calls to be made using Telephone over the internet protocols. The Home gateway would further communicate with and manage Video and DVD recorders and off air radios to record and provide entertainment as demanded by the home owners.

A Home Gateway could act as the intermediary between the Utility Companies and the home to encourage energy saving and implement demand side management where the Utility can turn off a non essential systems, as agreed by the home owner, during peaks in demand and then turn those services back on during low demand periods thus flattening out the demands and saving money on spinning reserves.

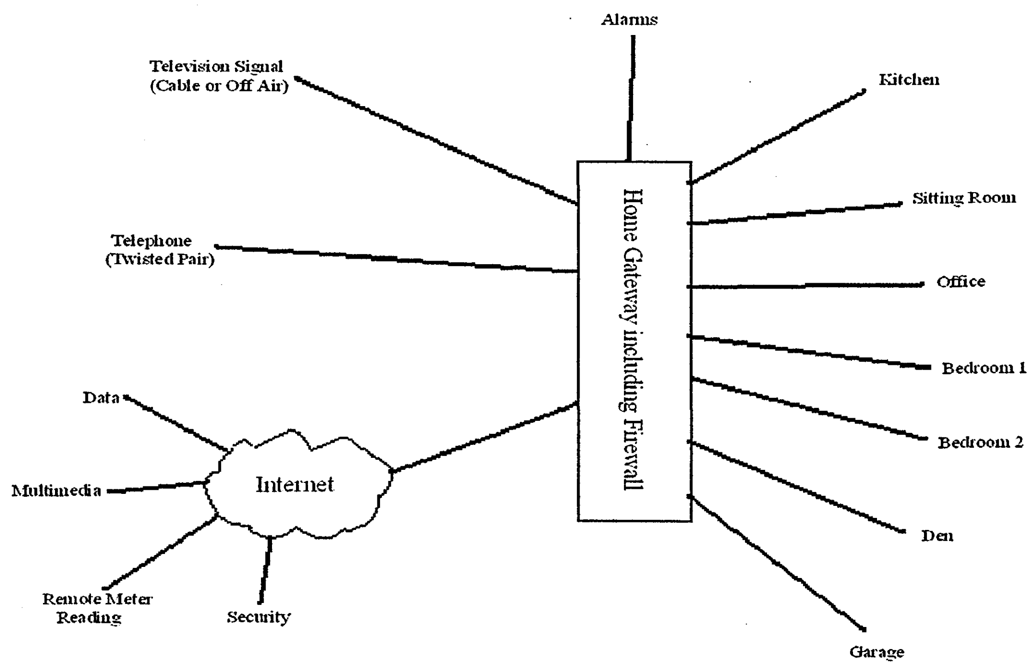


Figure 8 Home Gateway

2.3 Summary

Chapter 2 has covered the last kilometre problem by exploring traditional methods and then looking at new methods such as BPL, cable and fibre optic as well as wireless techniques. Chapter 2 then discussed home gateways and the reasons why the last kilometre problem has become more important. Chapter 3 will concentrate on Power Line Carrier and will explain the topology of the UK low voltage distribution system and then describe the regulations surrounding PLC in the European standard EN50065. Chapter 3 will investigate low and high frequency power line systems and detail some trials being carried out before discussing radiated noise and impedance of the mains distribution network.

Chapter 3 Power Line carrier Systems and Communications

3.1 Introduction

Chapter 2 explained the last kilometre problem and the reasons it has become more important such as home networks. Chapter 2 also covered ways of overcoming the last kilometre problem including cable, wireless and of course power line carrier. Chapter 3 will explain power line technology in greater depth including the topology of the low voltage distribution system use feed electricity to domestic premises and the regulations for low frequency PLC. Chapter 3 will also describe high and low frequency PLC systems and discuss the EMC issues and line impedances of such a system

Power Line Carrier satisfies many of the difficulties associated with the 'Last Kilometre' problem faced by those companies who wish to provide domestic and commercial premises with any form of electrical or electronic communications. The low voltage, 415v/240v in Europe and 110v in the USA, cabling goes to the vast majority of premises and the topology tends to be a tree and / or grid structure as shown in figure 9.

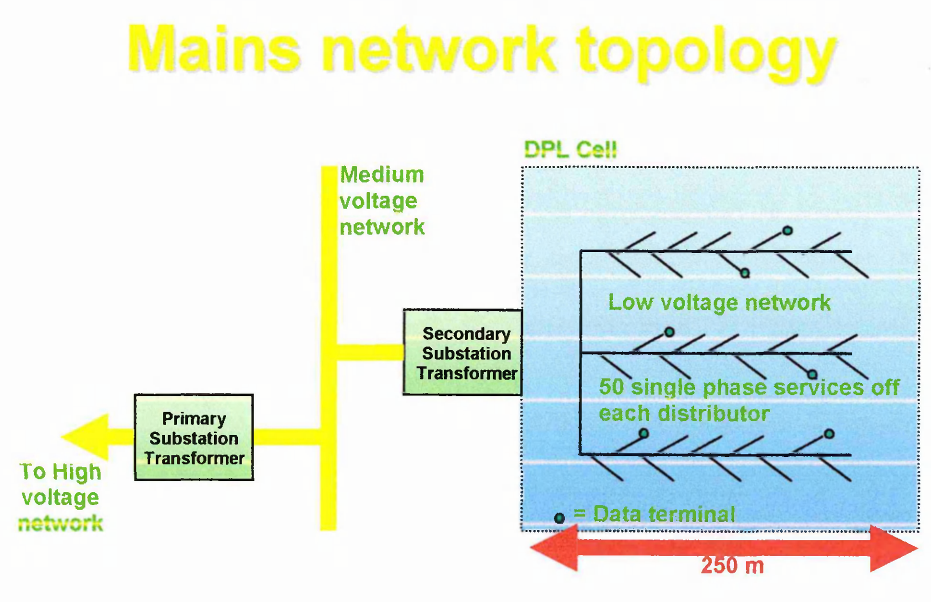


Figure 9 Example of a mains distribution system [15]

The tree topology affords the communications supplier one of the best topologies for incremental installation and expansion. The main disadvantages of a tree topology are the many joints and spurs which give rise to reflections and standing waves. Also a break in the electrical structure disconnects all of the sites after that break.

Another advantage of the PLC system over a telephone based system is that the supply system cabling is usually owned by the Utility reducing the need to lease lines to send / receive data. In Europe many of the substations have other communications connections to the sub station for command and control purposes which could be used to carry the PLC data as well. This added value system allows the Utility to offer the customers new functions such as ½ hourly meter reading (narrow band, low data rate) and up to the moment consumption readings (narrow band, low data rate) as well as in the longer term internet access (high data rate) and possibly even high definition video download (wideband, high data rate). However to achieve the above mentioned advantages some of the disadvantages of a PLC system listed in paragraphs 3.1.1 to paragraph 3.1.8 must be overcome.

3.1.1 Due to the high density of premises there are many spurs and connections giving rise to reflections and signal loss. These spurs will cause shadowing where some premises may not get the signal as expected.

3.1.2 Fitting new category 5 cables, coaxial cables or fibre optics to premises causes' high disruption to the traffic systems in the area in the form of road works and dug up pavements; also in rural areas the line lengths may be long enough to necessitate the use of repeaters or other signal regeneration techniques to ensure a usable signal reaches the premises.

3.1.3 There tends to be a high man made noise floor in urban areas along with other types of noise such as impulse noise and continuous tones of various frequencies sources such as switch mode power supplies.

3.1.4 The cross talk between premises can be high especially in urban areas where distances between premises is reduced this will get worse as more and more customers take up PLC systems.

3.1.5 Most customer sites tend to be different from all other sites due to the individual requirements of the occupiers and this will increase installation costs.

3.1.6 Within Europe the emissions of all electrical and electronic systems are limited by law, for instance when designing or using a PLC system in the frequency band 3 kHz to 148.5 kHz Cenelec standard EN50065 applies. Much work is at present being conducted to define the emission limits and test method for PLC systems in the frequency band 148.5 kHz to 30 MHz, now known BPL or Broad band Power Line.

3.1.7 Where the supply cables transition between overhead and underground routes additional attenuation of the PLC signal will reduce the range of the system again calling for repeaters.

3.1.8 When more information and entertainment channels are available to many sites the scope for fraud and theft is higher.

Regulatory Environment

The most relevant European regulations for power line carrier systems are detailed in EN50065. This European Standard is issued by Cenelec and covers the frequency band 3 kHz to 148.5 kHz. Cenelec's position in the regulatory landscape for PLT within Europe is shown in figure 10.

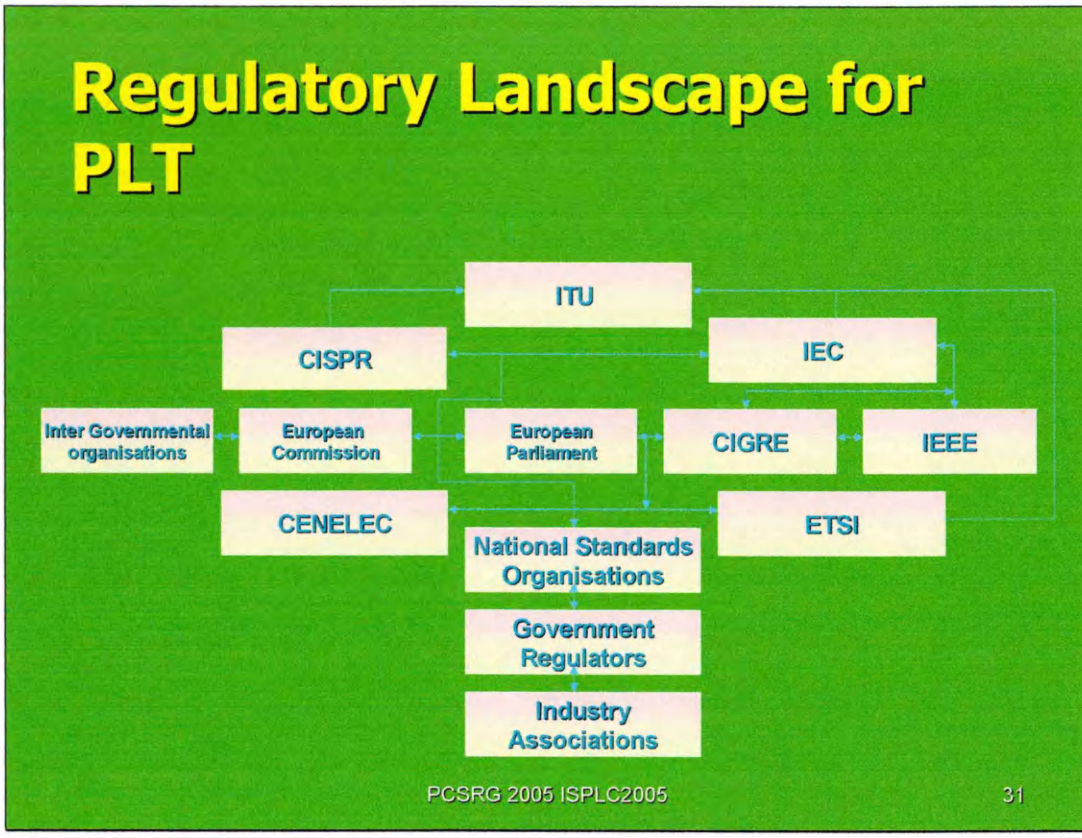


Figure 10 Regulatory environment for PLT [15]

The European standard EN50065 is at present split into 13 parts; these being:-

EN50065 Signalling on low-voltage electrical installations in the frequency range 3 kHz to 148.5 kHz.

EN50065-1 Part 1: General requirements, frequency bands and electromagnetic disturbances.

EN50065-2-1 Part 2-1: Immunity requirements for mains communications equipment and systems operating in the range of frequencies 95 kHz to 148.5 kHz and intended for use in residential, commercial and light industrial environments.

EN50065-2-2 Part 2-2: Immunity requirements for mains communications equipment and systems operating in the range of frequencies 95 kHz to 148.5 kHz and intended for use in industrial environments.

EN50065-2-3 Part 2-3: Immunity requirements for mains communications equipment and systems operating in the range of frequencies 3 kHz to 95 kHz and intended for use by electricity suppliers and distributors.

EN50065-4-1 Part 4-1: Low-voltage decoupling filters – Generic specification.

EN50065-4-2 Part 4-2: Low-voltage decoupling filters – Safety requirements

EN50065-4-3 Part 4-3: Low-voltage decoupling filters – Incoming filter

EN50065-4-4 Part 4-4: Low-voltage decoupling filters - Impedance filter

EN50065-4-5 Part 4-5: Low-voltage decoupling filters - Segmentation filter

EN50065-4.6 Part 4-6: Low-voltage decoupling filters – Phase coupler

EN50065-4.7 Part 4-7: Portable Low-voltage decoupling filters – Safety requirements

EN50065-7 Part 7: Equipment impedance

The frequency band 3 kHz to 148.5 kHz is spilt into two parts 3 kHz to 95kHz often called the access band in substations has been reserved for the use of the electricity suppliers and their licensees, while the band 95 kHz to 148.5 kHz is restricted to consumer use. The 95 kHz to 148.5 kHz band is further subdivided where the sub band 125 kHz to 140 kHz requires the use of an access protocol at 132.5 kHz as described in EN50065-1.

Other European and world standards are being researched that will cover the power line technology frequency band 150 kHz up to 30MHz to allow the use of high data rate transmissions demanded for fast internet access and high definition television. These will have to meet the CISPR 22 Information Technology Equipment Radio disturbance characteristics Limits and methods of measurement for Class B ITE equipment primarily for use in a domestic environment and Class A equipment all ITE equipment that does not meet the Class B limits, in the UK MPT1570 applies.

Other limits are under discussion in various technical committees in Europe and several limits have been proposed as shown in figure 11.

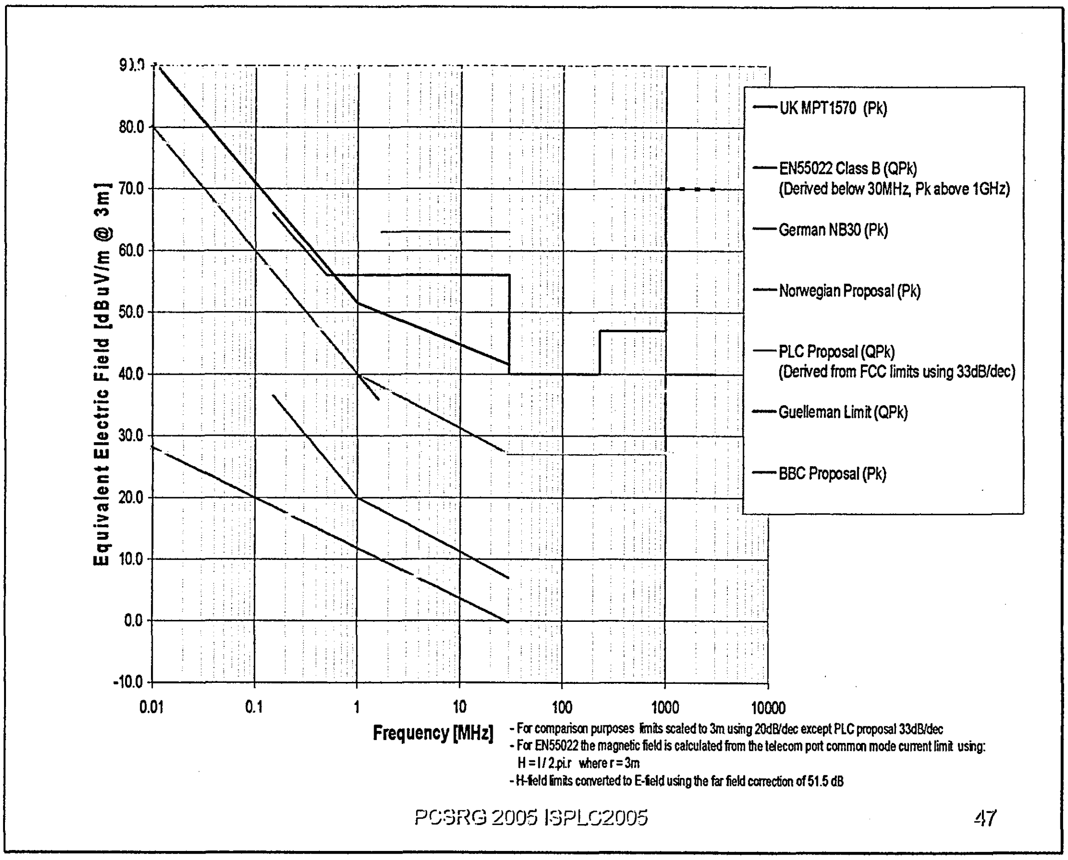


Figure 11 Proposed Radiated Emission Limits [14]

In the USA the radiated emissions from a PLC system is governed by Federal Communications Commission (FCC) Part 15. This allows power line carrier systems to operate in the frequency band up to 450 kHz.

The same communication requirements and patterns hold for PLC as for other communications systems so that the amount of data transmitted from a home as distinct to that transmitted to a home tends to be much less, even for Internet access and other entertainment's such as multimedia.

There are two distinct types of PLC system and these can be characterised by calling them low frequency communications systems, primarily aimed at the utilities and high frequency communications systems primarily aimed at the domestic and commercial communication needs, that is to provide an alternative to the PSTN local loop. The low and high frequency designations apply to the carrier frequency or centre frequency of the modulated signal that is transmitted over the power lines. The Low frequency communications are low data rate and primarily aimed at industrial usage such as automated meter reading (AMR), in house control and alarm systems. The high frequency power line systems tend to use the frequency band between 1 and 30 MHz with a lot of trials being conducted within the frequency range. These high frequency systems use a variety of modulation techniques and currently a spread spectrum system called Orthogonal Frequency Division Multiplexing (OFDM) is receiving considerable attention.

The power transmission system was not designed to transmit data; it has been optimised for the efficient transmission of mains power at 50 Hz. At other frequencies the transmission channel can be characterised as a noisy, both impulse and wide band, selective fading channel. A modulation system has been developed that can minimise the impact of selective fading in the transmission channel; this modulation system is OFDM. This is a digital modulation technique usually using a digital signal processor using the Fast Fourier Transform (FFT) to generate the multiple sine waves, typically over 1000, called sub-carriers that are precisely controlled for frequency, phase, and amplitude and modulated with the wanted data. Each sub-carrier can be modulated with various types of modulation and schemes such as QPSK through to 64 QAM are commonly used. The frequency spacing is Orthogonal in OFDM and is used to reduce or eliminate interference in the receiver due to non linearity's.

The advantages of OFDM are it can be spectrally efficient and as each carrier is modulated with lower data rates the system will perform well in multipath environments. The drawbacks are the transmission and reception equipments must be designed to cope with the large dynamic amplitude of the OFDM signal that is dependant on the number of carriers used. This is the Peak to Average Power Ratio (PAPR) [6] and is defined by in equation 1.

$$\text{PAPR (dB)} = 10 \log (N) \quad \ldots\ldots\ldots\ldots 1$$

where N is the number of sub-carriers

The transmission and reception equipment must be linear so as to reduce the chances of intermodulation distortion. This is increased with the proximity of so many carriers.

OFDM may be used to reduce the interference on important frequencies in the HF band by the technique of notching. This is where blocks of sub-carriers are suppressed so as to leave gaps in the OFDM signal for important HF communications channels. This technique has been shown to be possible but some residual interference remains. This tends to be due to intermodulation distortion and quantization noise within the transmitting equipment and channel non linearity.

3.3 Trials of power line carrier systems

There are some trials and installations of low data rate transmission systems where two frequency bands are allocated, 3 kHz - 148.5 kHz in Europe and 50 - 455 kHz in the USA. The European installations are governed by the EN50065 publication which dictates power levels and frequency bands.

There are also trials of high data rate power line carrier systems and a high frequency European standard is being developed for the frequency band 1 MHz – 30 MHz.

Several committees within the European Union, for example CENELEC Technical committee S/C205A, are looking at the various aspects of power line carrier and the uses to which it can be put. The committees have tended to concentrate on the lower frequency bands and low data rate signals such as meter reading and status and switching signals but are now looking at the ways High frequency Power line technology can be implemented without affecting the other users of the frequency bands 1 to 30MHz.

Low data rate systems can be used to transmit small amounts of data such as meter readings or error codes efficiently at low cost. The modulation used tends to be a simple robust system such as Frequency Shift Keying FSK making the transmission and reception equipment simple, low cost and reliable. As FSK is a narrow band technique it is not usually subject to selective fading and with the use of a robust protocol such as acknowledgement of signals and retransmissions can be quite reliable. The data is usually of such a nature that it may be set asynchronously with little impact on the user.

High data rate systems are used to transmit audio or video signals such as multimedia as well as other types of data; as such the data must be at the receiver ready for use as required by the user. The data must be sufficiently error free so that the user is unaware of any errors or missing packets of information. This means that the data must be sent at a rate that is sufficiently high to allow for retransmission of faulty packets or for large amounts of forward error correction data within the data packets. This calls for multiple megabits per second data rates and the use of higher frequencies in the HF band to transmit the signals on. Increases in BPL frequencies means that the line lengths of the mains distribution system start to be significant fractions of a wavelength of the BPL frequencies leading to increased chances that an interfering signal may be radiated. This radiation is due to the fact that the power distribution system may be viewed as a transmission line and this transmission line is not always a balanced system with the correct terminating impedance. Note that this applies to the far field. The transition between near field and far field is given by $2\pi r / \lambda$ where λ is the wavelength of the signal in question; in the near field the BPL signal is always to a varying degree an interference source as shown in figure 12.

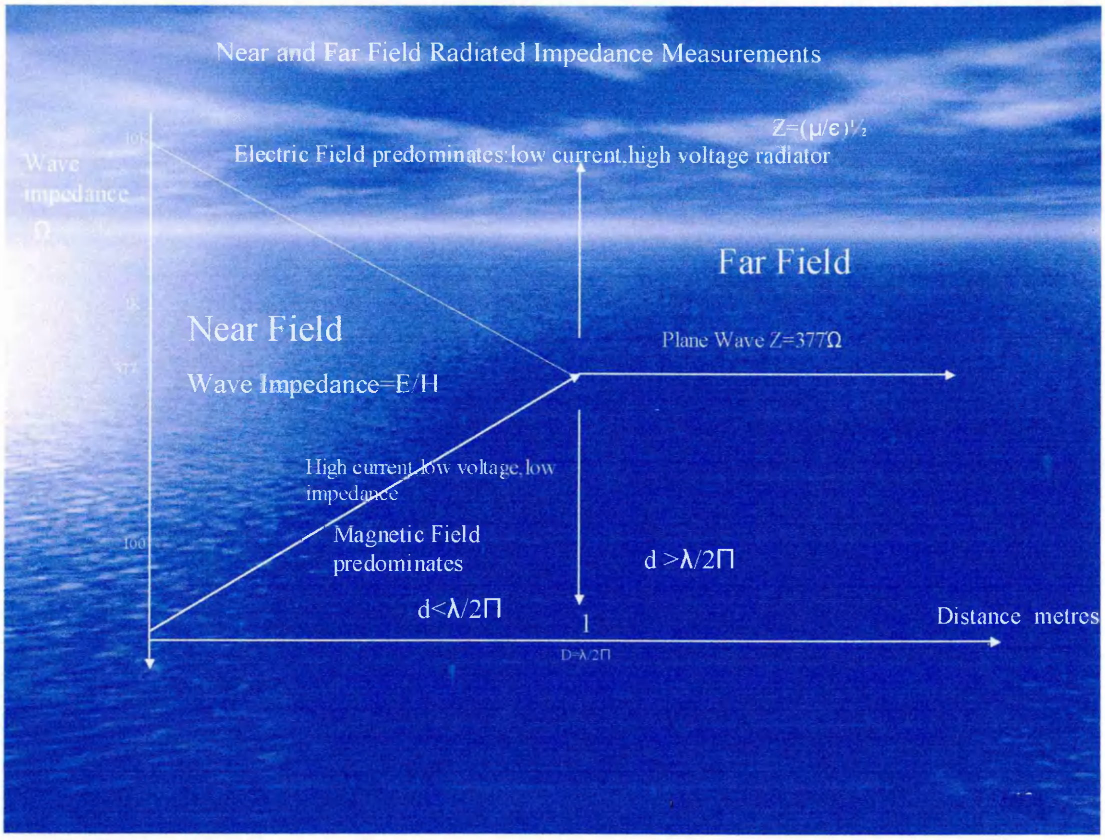


Figure 12 showing the transition between near field and far field [14]

Where most of the power distribution system in the UK is buried in the ground as shown in figure 13 it provides a good degree of insulation against interference of the HF band but it is when the signal comes out of the ground that it is likely to cause problems to other HF users.

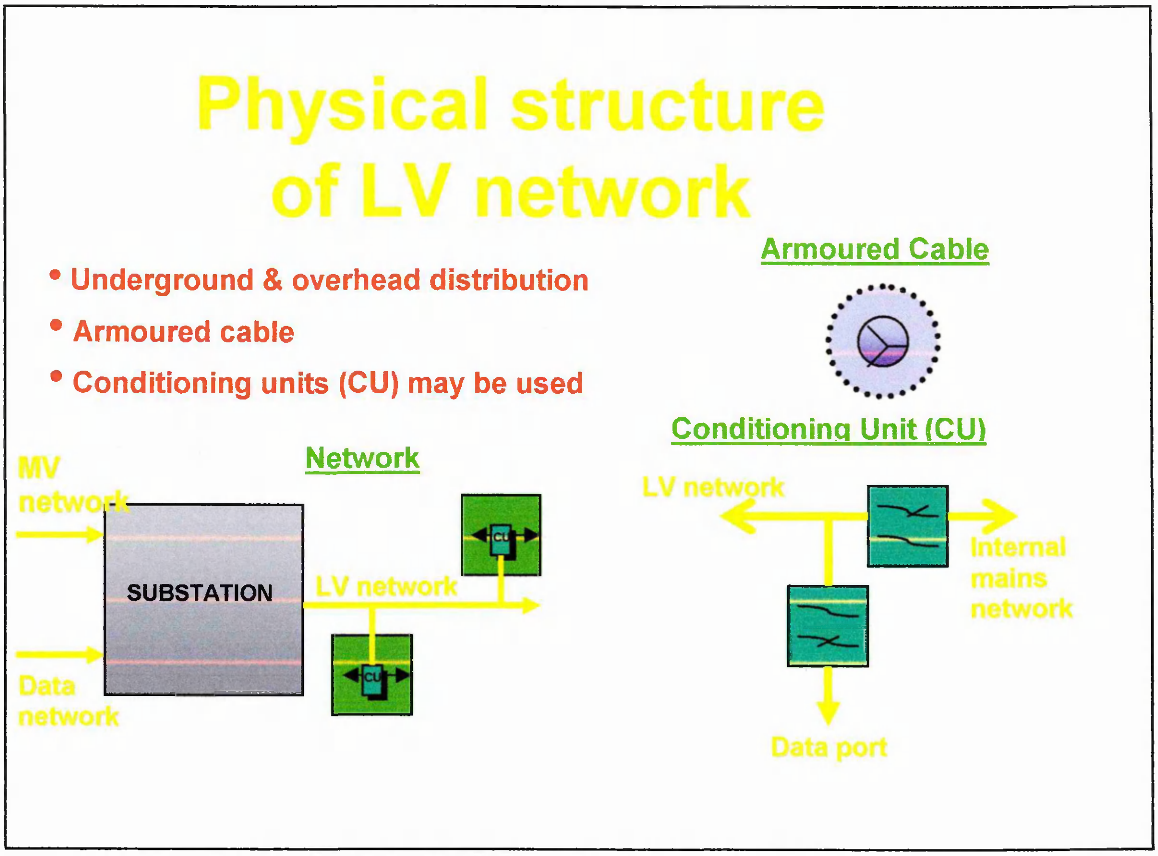


Figure 13 Physical structure of LV network [15]

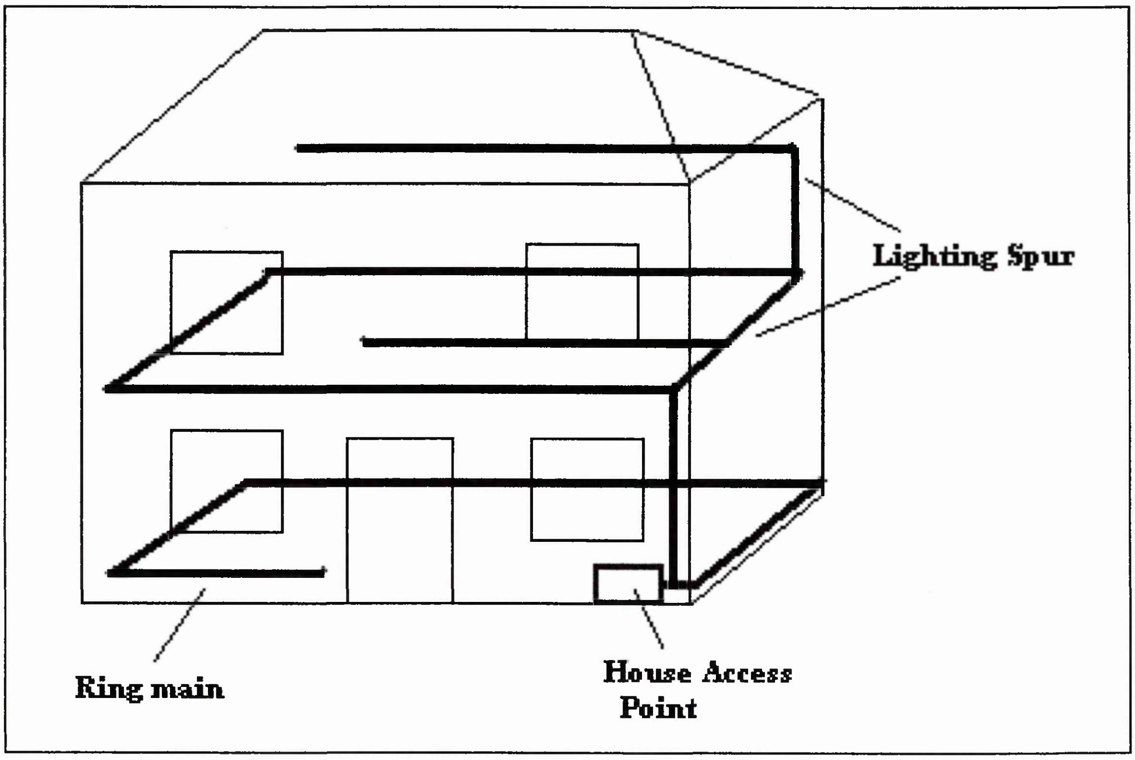


Figure 14 Sketch of house wiring system

A typical house wiring system consist of a ring main for both downstairs and upstairs with lighting spurs and of course trailing leads to various appliances as shown in figure14.

These cables are not correctly terminated transmission lines when a high frequency signal is considered. The wavelength of a signal is given by $c = f\lambda$ where c = the speed of light (3×10^8 metre per second), f = frequency of the RF signal and λ = wavelength of the signal.

Thus for a signal of 10MHz the wavelength is 30 metres while at 30 MHz the wavelength is 10 metres. However a full wavelength is not required to efficiently radiate a signal in fact a dipole at $\lambda/2$ or a ¼ wave monopole with ground plane are also efficient antennas and any significant fraction of a wavelength will radiate a signal to some degree.

3.4 Noise

The high frequency elements of the data signal radiate from the power lines and structures, such as streetlights, into the environment and potentially cause interference to other communication channels such as HF radio and long and short wave radio broadcasting. The potential EMC problems have yet to be resolved to the satisfaction of all interested parties but work is being conducted by the International Electrotechnical Commission (IEC) / Comité Internationale Spécial des Perturbations Radioelectrotechnique (CISPR) into characterising the potential interference and reducing it to an acceptable level.

Impulse and burst noise is generated when switches and breakers controlling electrical equipment switch on or off. The noise generated may be an impulse or spike if the switch action is fast thus minimising arcing. Some slower switches for example thermostats have a slow action and may generate a period of arcing causing RF noise. Tests at Eastern Electricity have shown little difference between customer load orientated noise levels day or night. This is in contrast to the experiences of the LF PLC systems that show an increase at night.

Steady state noise is caused by the power delivery system acting as an antenna and capturing radiated noise. CATV operators have gained experience in this type of interference and empirically predict that the average noise level varies with the square of the wavelength of the interfering signal and the typical field strength of an interfering signal at 10MHz is in the range 10 – 70dBµV/m. However the power distribution system is likely to respond in a different manner to that found by the CATV operators. The noise level at night in the frequency range 1.5 – 10 MHz will increase by the order of 20dB.

Impedance in houses, the maximum current at 240 volts allowed into a domestic site is 100 amps (set by HRC fuse conforming to BS1361) thus worst case input impedance into a home is 2.4 ohms resistive. The houses in a typical street in any UK town will be evenly distributed on all 3 phases thus the impedance presented to the sub station is all of the houses on that phase in parallel. Measurements in urban, sub urban and rural environments have shown the impedance of the power distribution system varies from less than 1 ohm up 8 ohms or higher. [5] These variations are dependant of position in the network and also vary with time of day and with the frequency as shown in figure 15.

Cumulative impedance, worst case into each house is approximately 2.4 ohms assuming that the length of the distribution spur between each site is 10 metres and that the line impedance of the supply cable at 1MHz is in the order of 12mΩ per metre [4] and 37mΩ at 10MHz [4]

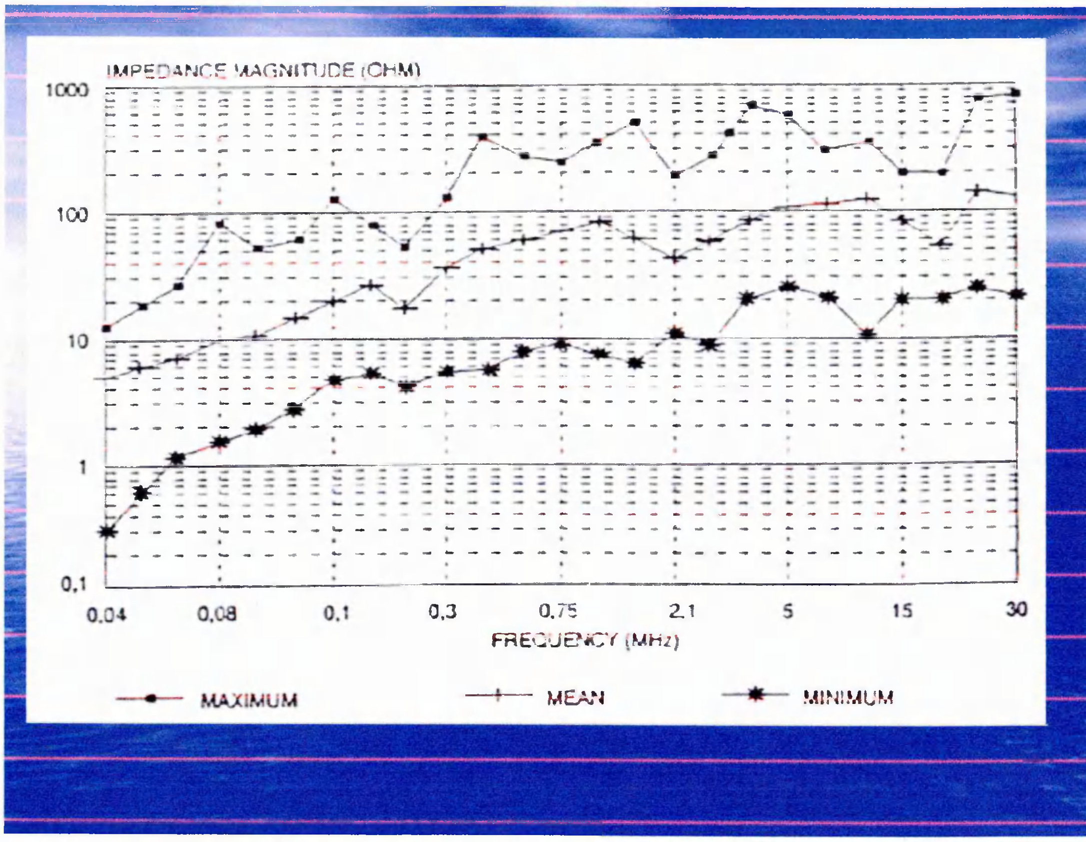


Figure 15 Impedance Variations versus Frequency [14]

3.5 Summary

This chapter has explained the difference between high and low frequency power line carrier systems and shown the topology of the low voltage distribution to domestic sites. The chapter has also discussed the regulations applying to low frequency power line and detailed some of the EMC issues experienced by all PLC systems but especially BPL. Chapter 4 will explain the theory of a radio wave using Maxwell's equations and then examine the regulatory environment before describing system protocols and modulation types. Chapter 4 will introduce polarisation and polar diagrams and discuss propagation over the last kilometre and link budgets.

Chapter 4 Radio Propagation

4.1 Introduction

The previous chapter has covered the background to power line carrier systems and explained the problems and regulations encountered by such a system. Chapter 4 will explain radio propagation especially how it affects a narrow band VHF radio link as used in automated meter reading systems. Chapter 4 introduces the theory and modes of propagation and Maxwell's equations. It then describes the regulatory landscape and system protocols before discussing polar diagrams, antenna gain and link budgets of a radio communications channel.

A radio channel is the path or paths that a radio signal travels between the transmit antenna and the receive antenna. The radio signal that is travelling along that radio channel is subject to attenuation due to the distance and possibly to phase changes due to the medium the radio signal is passing through. The radio channel is also subjected to other changes in its propagation characteristics over time due to 'fading'. Fading is comprised of several types of amplitude and phase variations including slow fading, Rayleigh and Rician fading plus multipath effects. Slow fading, some times called log normal fading is a slow effect as the name implies and is usually caused at higher frequencies by weather effects such as rain, snow, fog or troposphere effects.

The way a radio signal propagates through a medium such as air is governed by electric and magnetic effects that can be described by Maxwell's equations for electromagnetic waves.

Rayleigh fading occurs in cluttered propagation paths where there is no direct line of sight between transmitter and receiver so that the radio signal is reflected off one or more surfaces. The signal will arrive at the receiver via many different paths and will set up complicated standing wave patterns. If the receiver, or indeed one or more reflecting surfaces, is moving with respect to the transmitter then the receiver will encounter constructive or destructive interference; that is, at some points the reflected signals will add and at some points the reflected signals will cancel causing the receiver signal strength to fluctuate. The reflected signals will arrive at the receive antenna at different times according to the path lengths.

Rician fading is similar to Rayleigh fading except that there is an additional signal due to direct line of sight. The rate of change of amplitude and phase will be dependant on the relative amplitudes of the direct and reflected signals and the rate of movement of the reflector or indeed transmitter or receiver. Multipath effects are also caused by indirect signal paths between the transmitter and the receiver similar to Rayleigh and Rician fading but multipath effects occur where the propagation delay between the different signal paths is long compared to the transmitted symbol rate for digital modulation schemes and this delay is a significant proportion of a symbol bit period. Thus the higher the data rate of transmission the more significance multi path effects become requiring receivers to be fitted with equaliser circuits to help combat the multipath effects, this is because multipath causes inter symbol interference (ISI) which makes the data harder to recover which in turn calls for more error correction to be applied which uses up bandwidth.

4.2 Propagation Theory

A radio wave transmitted from an isotropic antenna moves away from the point source (isotropic means having uniform physical properties in all directions) as concentric spheres. As the distance increases the surface area of the sphere increases and the amplitude of the signal at a point on that sphere drops. A radio wave is a complex Transverse Electromagnetic (TEM) wave, i.e. it is an electric field and a magnetic field orthogonal (at right angles) to one another and orthogonal to the direction of propagation, also called a plane wave. These electromagnetic waves always maintain the same phase relationship and the ratios of the amplitudes also remains constant and travel at a speed of light c as shown in equation 2.

$$c = \frac{1}{\sqrt{\mu_o \varepsilon_o}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

A radio wave can be described by its wave length (λ), frequency (f) and by its velocity which in a vacuum is the speed of light c= 299,792,500 m/s. Speed of light, frequency and wavelength are related by expression 3.

$$c=f^*\lambda. \ \text{m/s} \ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

The radio wave can vary in amplitude, phase or polarisation.

4.3 Maxwell's Equations

A propagating radio wave can be considered as a time varying electromagnetic field that can be fully described by Maxwell's equations [8]. These equations were later put into the simpler vector form by Heaviside and Gibbs.

$$\nabla \cdot \mathbf{D} = \rho \text{ or } \nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon} \ldots\ldots 4$$

$$\nabla \cdot \mathbf{B} = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots 5$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \ldots\ldots\ldots\ldots\ldots\ldots 6$$

$$\nabla \times \mathbf{H} = J + \frac{\partial \mathbf{E}}{\partial t} \ldots\ldots\ldots\ldots\ldots\ldots 7$$

$$\nabla \cdot \mathbf{J} = -\frac{\partial \rho}{\partial t} \ldots\ldots\ldots\ldots\ldots\ldots 8$$

where $\nabla \times$ is the curl operator, $\nabla \cdot$ is the divergence operator, **E** is the electric field strength in V/m, **H** is magnetic field strength in Amps/m, **D** is electric flux density in C/m^2 sometimes called electric displacement field, **B** is magnetic flux density in Tesla, and in free space permittivity $\varepsilon = \varepsilon_o$, ρ is charge density and permeability $\mu = \mu_o$. Note bold letters express a vector.

These equations come out of the insight by James Clerk Maxwell and the earlier work on static fields by Coulomb, work by Gauss on electric field strength and flux density, equation 4, on magnetic flux, equation 5, Faradays law on electromagnetic induction, equation 6 and finally a modified version of Amperes law on time varying electric fields and the production of time varying magnetic fields, equation 7.

Two points to note are that a static electric field can exist without a magnetic field such as around a static point charge and secondly that a current carrying conductor may have a magnetic field without an electric field.

Given a point charge Q Coulombs law states that the force acting on another point charge q placed in the vicinity of Q is given by equation 9.

$$\mathbf{F} = \frac{Qq}{4\pi\varepsilon R^2}\mathbf{a}_R \text{ Newtons} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 9$$

where $\varepsilon = \varepsilon_r\varepsilon_o$ is the permittivity of the medium in Farads per metre

and as

$$\mathbf{E} \text{ is equivalent to } \frac{\mathbf{F}}{q} \quad \text{Newtons per Coulomb}$$

for a point charge the electric field strength is given by equation 10.

$$\mathbf{E} = \frac{Q}{4\pi\varepsilon R^2}\mathbf{a}_R \text{ V/m} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 10$$

Gauss's law states that the net electric flux radiating from a closed surface surrounding a point charge is directly related to the charge contained by that surface and by extension to the electric flux in the vicinity of a collection of charges.

Electric flux density **D** is related to electric field strength **E** by equation11.

$$\mathbf{D} = \varepsilon\,\mathbf{E} \text{ coulombs/metre}^2 \quad \ldots\ldots\ldots\ldots\ldots\ 11$$

Another of Gauss's law states that for any surface that encloses a volume V the number of magnetic lines entering the volume will be equal to the number of magnetic flux lines leaving the volume and that magnetic flux lines are continuous and form closed loops or infinitely long lines and that magnetic monopoles do not exist.

Faradays law of magnetic induction states that a time varying magnetic field will produce an electric field or another way of looking at it is if the magnetic flux going across a closed electric circuit changes an electromotive force EMF is produced as shown by equation 12. Note that the electric field so set up tends to oppose the change in the magnetic field.

$$V = -\frac{d\Phi}{Dt} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 12$$

where V = volts and Φ = magnetic flux in webers

Amperes law describes the generation of a magnetic field from conduction current. Ampere's law states that the current enclosed by a tangential magnetic closed path is equal to the magnetic field strength around that closed path. Maxwell changed Ampere's law to show that time varying electric fields act like currents and produce time varying magnetic fields.

Lorentz force equation states that the force exerted on a moving charge particle by an electric field and magnetic field is given in equation 13.

$$\mathbf{F} = q\mathbf{v} \times \mathbf{B} \text{ newtons (N)} \quad \ldots\ldots\ldots\ldots\ldots\ldots 13$$

where q = point charge, **v** = velocity and **B** = magnetic field

Now in a non conducting region the convection current density $\mathbf{J}_{convection}$ is given in equation 14.

$$\mathbf{J}_{convection} = \rho\mathbf{v} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 14$$

where ρ = charge density in coulombs/metre and **v** = velocity in m/s and the total current density is given in equation 15.

$$\mathbf{J} = \mathbf{J}_{convection} + \mathbf{J}_{conduction} \quad \ldots\ldots\ldots\ldots\ldots 15$$

So that charge and current are related by the continuity equation 8.

So Maxwell proposed that in a time varying field the rate of change of convection current density produces a similar time varying magnetic field. Thus a time varying magnetic field will set up an electric field in any medium and this is the basis for electromagnetic wave propagation where the electric and magnetic fields produce each other in the absence of other sources.

4.4 Modes of Propagation

There are 5 main modes of radio wave propagation and these are Free Space, Line of Sight (LOS), Ground Wave, Ionospheric and Tropospheric, there are other modes such as sporadic E, meteor scatter, trans-equatorial as referred to in appendix 2.

Free Space propagation is where there are no large objects near the transmitting and receiving antennas that could affect them or in the signal path to affect the radio wave. Line of site is as the name implies where the transmitting antenna is in direct line of sight with the receive antenna. Ground wave propagation is where a propagating wave follows the curvature of the earth due to currents in the ground slowing down and tilting the wave front. It is made up of a direct wave and a surface wave that extends up about one wavelength from the ground. This mode is usable below about 3MHz and tends to be used for Medium Frequency radio broadcasts, above these frequencies the attenuation becomes to large for good communications, as shown in figure 16.

Ionospheric propagation is where the path and amplitude of the radio wave is modified by the action of free electrons in the upper atmosphere. These free electrons are released by energy from the sun striking the upper atmosphere and form layers as shown in figure 17

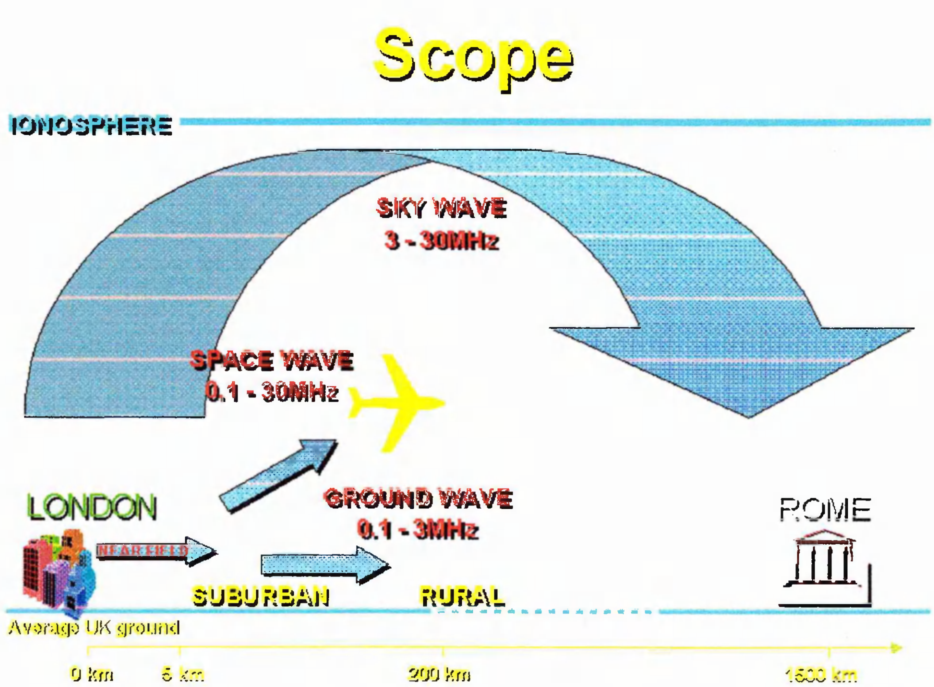


Figure 16 Propagation paths [14]

The density of free electrons is greatest in the middle of each Ionospheric layer and as the radio wave strikes the free electrons they re-radiate the signal, this causes the radio wave to be refracted away from the greater ionisation. This propagation mode tends to be used for long distance HF communications.

Tropospheric propagation is where the radio signal is affected by the variation of the refractive index of the troposphere just above the earth's surface (up to 2km). The effect is most pronounced above 30 MHz. A high energy radio beam is transmitted into the sky and some of the signal is refracted back. This mode of propagation is a way to use VHF and UHF bands at greater distances that LOS for example between Gibraltar and Malta.

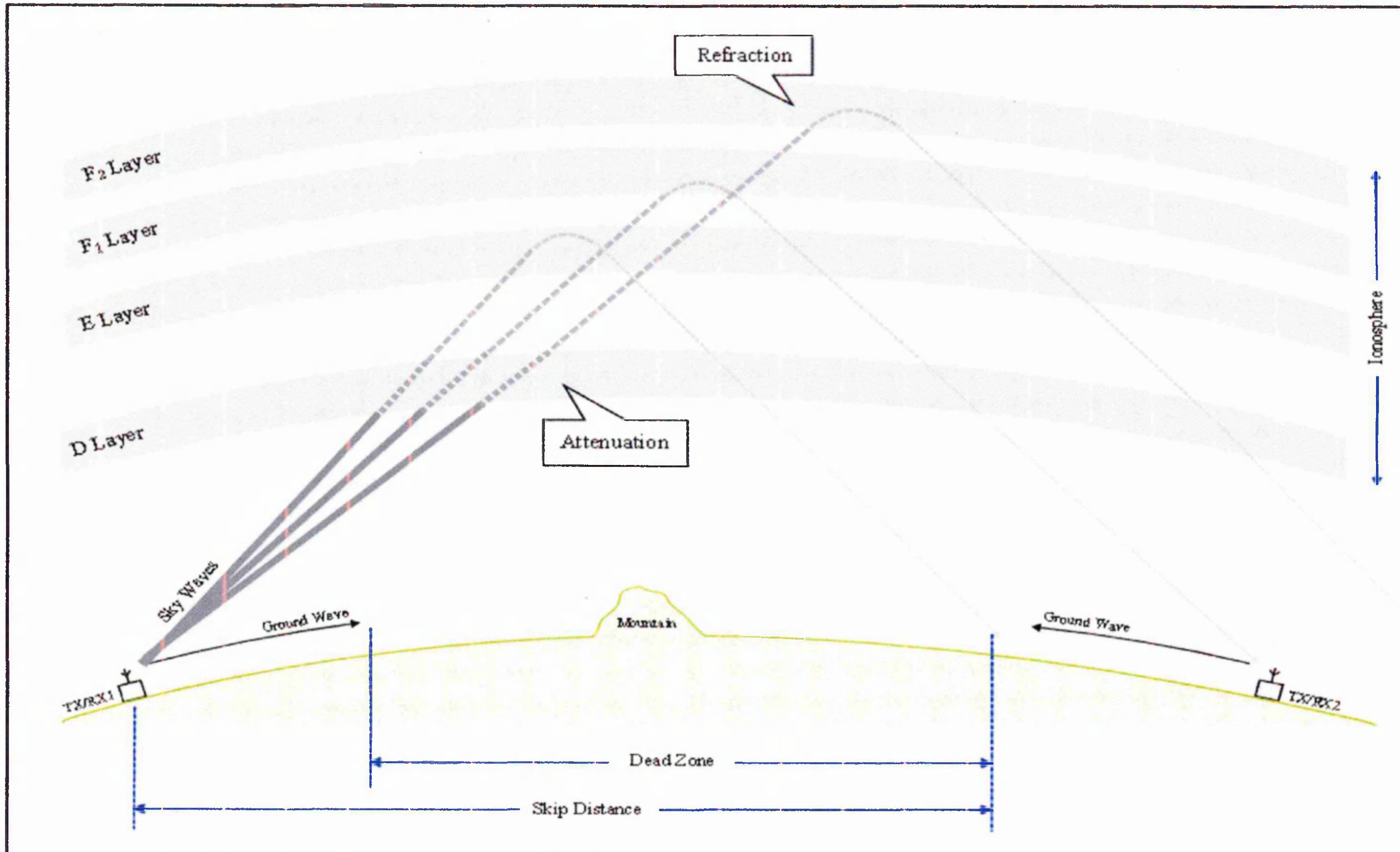


Figure 17 Ground wave, refracted signals and ionosphere

The lowest Ionospheric layer in the atmosphere is the D layer, see figure 17, and while it does produce some refraction due to its great concentration of ionised atoms and free electrons it mainly attenuates the radio waves passing through it. The D layer tends to disappear after sunset and reappear at dawn. The next layer up is the E layer; radio signals with a sufficiently high frequency will pass through the D layer and be refracted by the E layer. Even higher frequency signals will pass through both the D and E layers and be refracted by the F layer. During the day the F layer splits into two and both layers will refract radio waves. The F2 layer being the highest will give the most range. If the frequency of the radio waves is increased there comes a point where insufficient refraction takes place and the radio wave is not returned to earth. This frequency is called the Maximum Usable Frequency (MUF). At even higher frequencies the radio signal will pass straight through all of the layers and may be used to access satellites. The height and density of all of the layers of the Ionosphere are affected by the time of day as well as the condition of the sun. Most of the energy that causes the Ionosphere comes from sun spots and they follow an eleven year cycle. The Lowest Usable Frequency (LUF) is dependant on many factors including the configuration of the transmit and receive sites as well as transmit power and the state of the D layer which attenuates lower frequencies more than higher frequencies and the amount of noise in the vicinity of the receiver.

When radio signals are transmitted via the ionosphere there is an area between where the ground wave can last be received and where the refracted wave can be received where no signals from the transmit station can be picked up. This is called the dead zone. By varying the frequency and power of the transmitter it is possible to change the refracting layer in the ionosphere used by the radio signal and change the skip distance which will change the size or location of the dead zone, as shown in figure 17. These modes of propagation can be important as they will transmit unwanted HF signals as well as wanted signals. The BPL systems use the frequency band 1 MHz to 30 MHz and may cause interference some distance away from the interfering source.

Radio waves will travel in any propagation mode that is possible. This means that some paths will be of much greater length than others and this will in turn lead to constructive and destructive addition at the receive antenna. When the signals arrive in phase they will add and when in anti-phase they will subtract and cancel out. This can lead to fluctuations in signal strength of 10's of decibels and is called fading.

The path loss in free space between two points can be predicted and is expressed as a power ratio in decibels as shown in equation 16.

Free Space Path Loss (dB) = $32.45 + 20\log_{10}f + 20\log_{10}d$ 16

where f is frequency in MHz and d is distance in Km.

The Free Space prediction is rarely of use as the ground and any structures, blockages or other clutter will reduce the range.

4.5 Restrictions and Legal Requirements

The Radio spectrum used for communications extends from approximately 38 kHz up to, at the present time, 100 GHz. While this seems to be made up from many communication channels, each channel uses between 3 kHz and 20 MHz of bandwidth only certain bands can be used for specific applications. The band from 60 kHz up to around 30MHz is primarily used for long distance communications around the world as shown in figure 18.

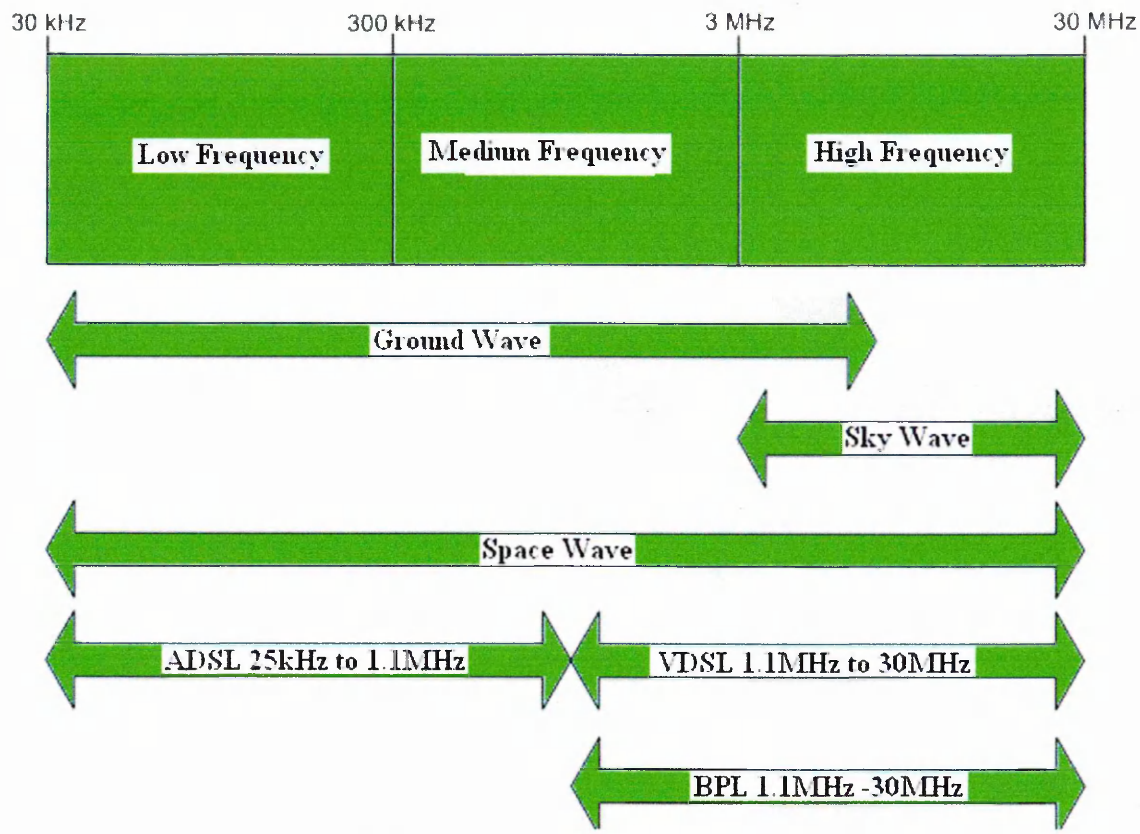


Figure 18 Frequency Spectrum used for BPL

It would be inappropriate to use this band for say local links to an electrical substation, as the next country would be picking those signals let alone the next substation. The bands above 2-3GHz tend to suffer most attenuation due to obstructions such as hills, buildings, trees and even the air attenuates some frequencies so these are used only for 'line of site' (LOS) links and small cell sizes. The spectrum that is mainly used for radio links over 'the last Kilometre' is from approximately 30 MHz to about 3GHz. This band of frequencies is heavily used by many different operators and must be controlled on an international scale, as radio signals do not respect country borders. The major agencies that manage the radio spectrum are shown in figure 19 and listed below.

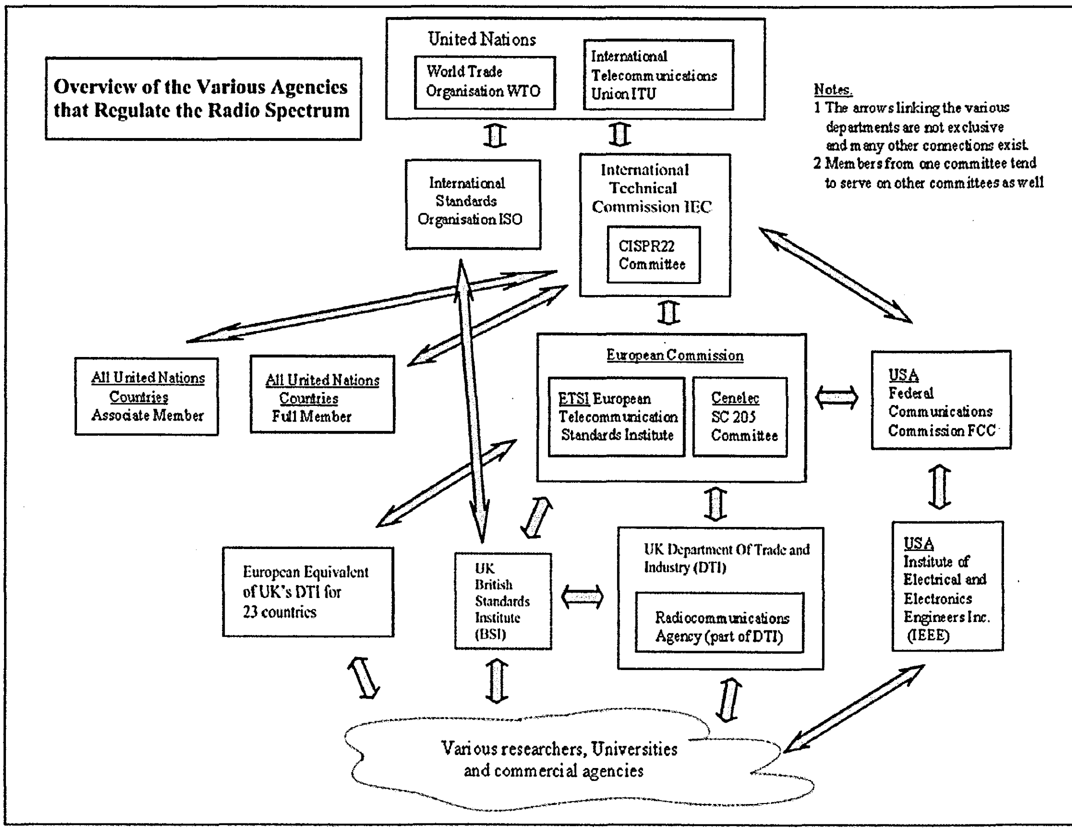


Figure 19 Overview of the various agencies that regulate the radio spectrum

Note that besides meeting the requirements for radiated emissions radio equipments may be required to meet compatibility requirements laid down by commercial organisations to aid interoperability.

The International Telecommunications Union (ITU) was formed in 1865 and is based in Geneva Switzerland. The main role of the ITU is to "maintain and extend international cooperation among all member states of the union for the improvement and rational use of telecommunications of all kinds". The ITU operates as an international organization within the United Nations System; under the Economic and Social Council as does the World Trade Organization (WTO); all ITU recommendations are non - binding, voluntary agreements. The section of the ITU that is concerned with the Radio Spectrum is the ITU-R or ITU Radio communications Sector. The specific role of the ITU-R is to allocate frequencies and band / frequency usage to minimise the interference between different countries. The ITU-R generates specifications and operational procedures for terrestrial and space based wireless systems. It carries out technical studies, with the aid of experts drawn from industry and academia, which are presented in regular conferences. The radio regulations decided at these conferences are published in a book and the ITU-R aids in the complex inter government negotiations to implement these regulations.

The International Technical Commission (IEC) was founded in 1906 and has more than 60 full member countries. The IEC is a global organization that generates and publishes international standards for all electrical, electronic and related technologies. The International Standards Organization ISO (formed in 1947) performs the same duties for all other technical standards. The IEC is an organization made up of full and affiliate member countries. Full members participate in preparing standards and have voting rights. Affiliate members can still participate in the generation of standards but have no voting rights and do not have the financial burden of full membership. The IEC and ISO are endorsed by the World Trade Organization (WTO) via the "WTO Technical Barriers to Trade Agreement". IEC standards may be adopted by any country if a member or not and adoption of a standard is entirely voluntary. The generation and adoption of standards is by consensus of the members of the IEC. Note that the IEC allows any governmental or non-governmental organization to participate in the preparation of standards.

European Committee for Electro-technical Standardization (Cenelec) was formed in 1973 and is an officially recognised European standards organization of the European Commission. Cenelec has a General Assembly made up of delegations from all of the EEC member countries. There is an Administration Board and a Technical Board. The Technical Board oversees the work of the various Technical Committees and Working Groups and defines the titles and guidelines for those committees and groups. The Technical Committees prepare the standards within the defined guidelines, they also take into account any work done by the IEC and other standards bodies or technical committees. Technical Committees may set up sub-committees that will work on separate areas within the standard or may take different timescales to complete the work. The Technical Board can also set up Task Forces or Working Groups to undertake specific tasks in a given time frame. Another link to the work of IEC/ISO is provided by the Reporting Secretariat who monitors the work of the IEC/ISO and reports this information to the Technical Board.

Radio communications Agency, part of the UK Department of Trade and Industry is tasked with implementing the UK government's control of the radio spectrum. The spectrum allocations of frequency usage and RF radiated power levels within the UK are decided by the government in consultation with the ITU-R, Radio communications agency, the European Commission and any other interested parties. The Radio communications Agency manages the radio spectrum by licensing certain bands and monitoring spectrum usage. To use a licensed band the user must demonstrate that the equipments will meet certain standards of power output, frequency control modulation type and other factors as laid down in a Radio communications MPT specification or ETSI specification. Licensed test houses will perform tests to these standards, for a fee.

European Telecommunications Standards Institute ETSI is a non profit making organisation recognised by the European Commission. ETSI is based in Sophia Antipolis in the south of France and has 874 members from 54 countries. ETSI main aim is to develop a wide range of standards and operating procedures as Europe's contribution to world standards.

The Federal Communications Commission (FCC) is an independent US government agency formed in 1934.The FCC is charged by the US Congress to regulate interstate and international communications and is directed by 5 commissioners appointed for 5 years by the US President. The FCC is organised by function and is made up of 6 bureaus and 10 staff offices that process license applications, analyze complaints, conduct investigations, develop and implement regulatory programs and enforce regulations. Through its International Bureau the FCC takes part in the organisation of Radio spectrum usage throughout the world by attending World Radio Conferences and monitoring the World Trade Organisation.

4.6 Modulation Bandwidth and Noise

The modulation type along with the information to be transmitted (amount of data and rate) will affect the bandwidth of the transmit signal and of course the required bandwidth of the receiver. The transmitted signal must fit into the allowed channel with no interference caused to the adjacent channels or any other radio user. There are many modulation methods now available that will use the available channel bandwidth efficiently but their adoption may increase the complexity and therefore cost of the terminals, the achievable range is also likely to be impacted as the requirement in the receiver to accurately reconstitute the information into usable form will require a signal to noise ratio much higher than the simpler modulation schemes. The signal to noise ratio is a measure of how large the signal is compared to the noise at the input to the detector or demodulator in the receiver for a specified or required quality of service (QoS) BER, the signal to noise ratio is usually expressed in decibels.

Noise is made up from noise received at the antenna and noise generated in the transmitter and receiver. The external noise is made up of cosmic noise received from space and man made noise and both of the noise sources vary with frequency. The amount of noise at the detector is also affected by the noise bandwidth of the receiver; this noise bandwidth tends to be wider than the signal bandwidth as it is the cumulative integral of all of the receive filters to that point. Note that the man made noise is much higher in urban areas than in rural areas, also the noise generated in the receiver and the transmitter is caused by the ambient temperature exciting the atoms that make up the components in addition to variations in power rails and local oscillator phase noise.

Modulation techniques can be used to reduce fading and other effects caused by 'Multipath' which is where the radio signal between transmitter and receiver takes several different paths. The paths can be frequency dependant (more pronounced in wide band signals) or of greater length causing time distortions or both. These effects can be overcome using wide band techniques such as Orthogonal Frequency Division Multiplexing (OFDM) or Direct Sequence Spread Spectrum (DSSS) with high processing gain.

4.7 System Protocols

The British Standards Institute (BSI) deals with the standards in the UK. IEC CISPR has designated a small band of frequencies centred on 184MHz and 433.92MHz and 868MHz to be used for gathering of meter information by radio link within the European Union. In the USA the main frequency of interest to radio meter readers is 915 MHz. The power transmitted is also regulated as is the modulation type; the maximum power is 100 milliwatts (or 0.1 watt or 20dBm) at 184 MHz, 10 milliwatts (10dBm) at 433.92MHz and up to 1 watt at 915MHz but spread over at least 6 MHz of bandwidth in a spread spectrum system; note this can be a fast hopping system or a direct sequence spreading system.

The bands of frequencies that may be used, centred on the frequencies mentioned above, are approximately 1MHz wide, except at 915MHz where the ISM (Instrument, scientific and medical) band is 902 MHz to 928 MHz; these bands are further sub-divided into sub-bands or channels. The radio signal including all of the information modulated onto the carrier must fit into the sub-band so that it causes no interference to the adjacent channels or to other users at other frequencies especially at double and treble the carrier frequency (second and third harmonic). The centre frequencies were chosen so that the main transmission mode is direct line of site. The radio channels that can be used for utility meter reading are listed in Table 1.

Frequency	Wavelength	Usage
183.5-184.5MHz	1.6m	Licensed utility meter reading channel in UK
433.92MHz	691mm	Licensed utility meter reading channel in Europe and some parts of Asia and South America. Secondary use as Amateur Radio band
866-868MHz	345mm	Non Licensed band, may be used for utility meter reading channel in UK and Europe
902-928MHz	325mm	FCC Part 15 ISM (Instrument, Scientific and Medical) band. Spread Spectrum meter reading channel in USA

Table 1 Frequencies and usage of 'Meter Reading Bands'

The selection of which radio channel to be used will be dictated by the regulations as will to a certain extent the modulation type, allowed power radiation and channel width/spacing. The type of modulation along with the amount of data and channel bandwidth will dictate the length of time each unit, in this case each utility meter will need to occupy the radio channel to transmit the information. The required signal to noise for a given modulation type and receiver design along with the antenna gain and permitted radiated power will dictate the achieved range between utility meter and node. Transmitter on time is often regulated so that the radio channel is mostly unused allowing for easy access; this is called duty cycle and is quoted as 2 seconds in every 2 minutes for example.

A method to characterise the radio channel for data transmission is to measure the Bit

Error Rate (BER) or Frame Error Rate (FER), where the later is dependant on the protocol. BER is specified as a percentage or as the number of bits transmitted before an error bit is received. So 10^6 would imply that you would receive one error bit for every 1,000,000 bits received. Without error detection and some form of correction even that one error bit could be catastrophic to the message. To enable error detection it is usual to add extra data to the message in the form of a Cyclic Redundancy Check (CRC) check or some Forward Error Correction Coding (FEC) which can be used to restore the message content or at the least recognise that the message is corrupted. These techniques of course extend the length of the message; however if the message is short for example a utility meter reading once an error is detected it is often easier to retransmit the whole message than to transmit large amounts of Forward error correction.

As there is often only one channel available for transmissions in either direction (called a simplex channel) some form of collision avoidance is required. This may take many forms such as token passing or timeslot allocation or poling; these are a form of time division multiple access (TDMA). If more than one frequency channel is available then a duplex channel can be set up or there may be a special channel to pole the utility meters that would then respond on a separate frequency channel, this could be deemed a form of frequency division multiple access (FDMA). There is another technique called Code Division Multiple Access (CDMA) that is associated with Spread Spectrum systems. This is where the radio signal is spread out in frequency across a wide bandwidth (usually 6 MHz or more) by the use of a spreading code. Another signal using a different carefully selected spreading code can occupy the same channel with little co-interference. Once the transmission / collision avoidance method has been adopted the statistics of the channel usage can then be calculated and the collision avoidance schemes effectiveness assessed.

4.8 Polarisation and Polar Diagrams

A radio wave is made up of an electric field and a magnetic field; these are at right angles to each other and at right angles to the direction of propagation (this is called a plane wave). A rod or stick like antenna can be used to capture the electric field of that plane wave and a loop is mainly used to capture the magnetic field of the plane wave. The polarisation of the radio wave is defined by the E field thus the 'stick' antenna is mounted vertically with respect to the earth's surface to receive a vertically polarised radio signal and mounted horizontally to receive horizontally polarised radio waves. Note that a vertically polarised antenna will not receive any horizontally polarised signals. Most radio systems specify vertical polarisation as this orientation of signal is less affected by the ground and provides the longest range. As a radio wave travels between the transmitter and receiver it is subject to reflection, refraction and scattering that may cause the polarisation to skew from the original orientation. A further type of polarisation called circular polarisation can be used to reduce this problem but circular polarisation calls for special beam antennas and tends to be used primarily for point to point or satellite links.

Many books [7] [8] talk about an isotropic radiator, this is a point in space that radiates a radio signal equally in all direction; in the real world this is not achievable. The books also talk about a free space model where the formation and radiation of a radio wave from an antenna is unaffected by any structures or by the ground and this too is not achievable except in extreme cases, for example satellite to satellite. The vast majority of radio systems use a version of a short dipole antenna which has two rods mounted end on to each other, each just under a ¼ wavelength long; another common antenna is a ¼ wave monopole but this requires an adequate ground plane. In fact all antennas can be modelled by either a combination of short dipoles or small loops or a mixture of both.

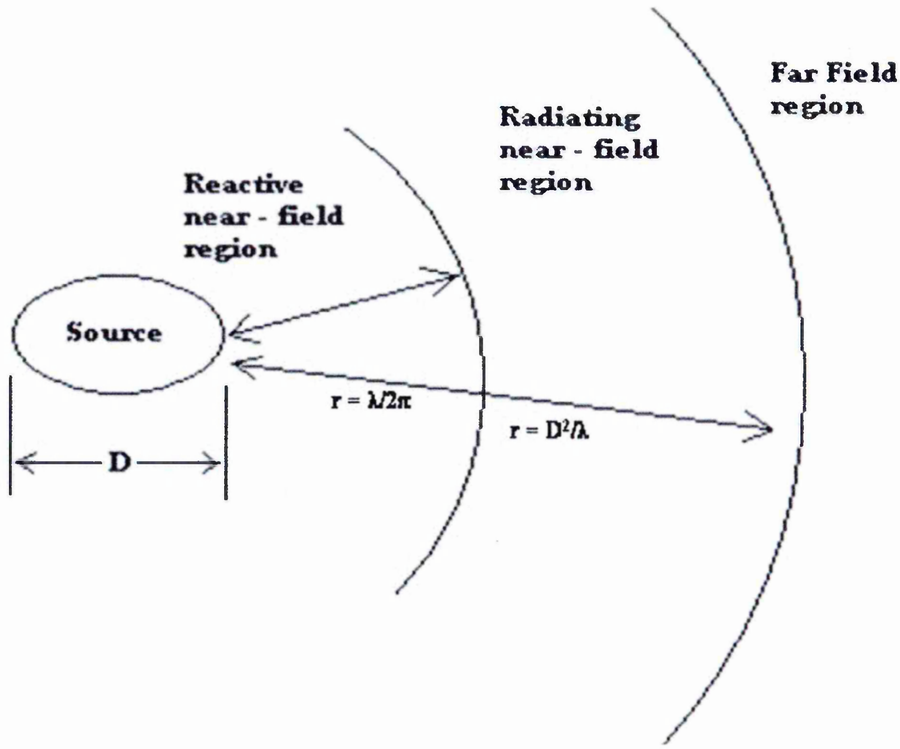


Figure 20 showing near and far field boundaries

There is often mention of near and far fields, these are defined by the wavelength of the radio wave and the size of the radiating source and shown in figure 20. The 'reactive near field' is a concentric sphere (dependant on the antenna) around the source at a range $r = \lambda/2\pi$, where λ is the wavelength of the propagating wave. As electromagnetic energy is stored in the electromagnetic fields this region is of most importance to EMC and health and safety engineers. The radiating near field extends out to approximately $r = D^2/\lambda$, where D = size of radiating source and $D \ll \lambda$. In this region propagation predictions are not possible. The far field starts at the $r = D^2/2\lambda$ boundary and this is used for radio communications.

The range that a radio link can achieve is dependent on many factors. In the urban environment, where there are a lot of obstructions the height of the antennas is of prime importance. An omni directional antenna that is above the roof tops will have good coverage as shown by the polar plot of field strengths at given ranges. The resulting ‘polar diagram’ of signal strength versus range will not be the perfect circles at specific ranges as shown in figure 21 and listed in the specifications for the antenna due to the obstructions in the environment.

The ‘dent’ at the 090° axis in figure 22 is caused by an obstruction in the path of the radio signals. This obstruction could be any thing from a metal pole to a building or even a tree depending on frequency, humidity and other factors. The range will be reduced in this direction. When the antenna is mounted in a shrouded or poor position the range and coverage can be severely diminished.

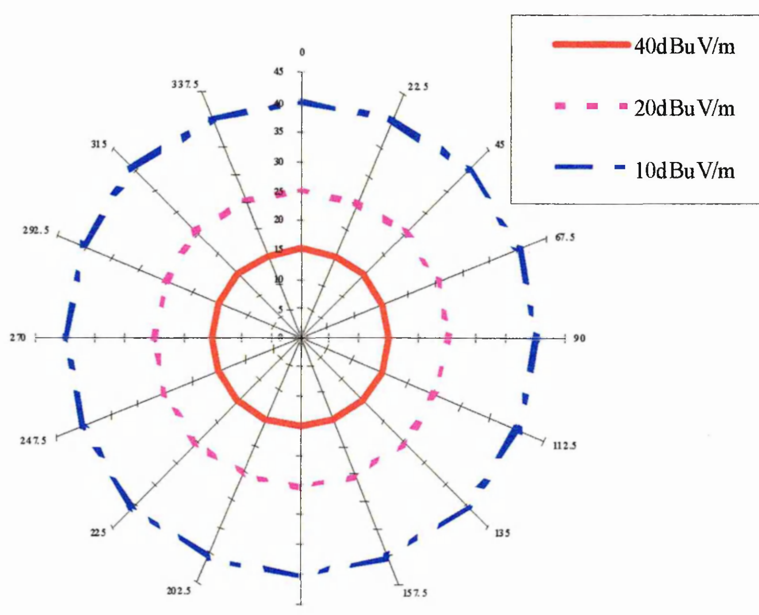


Figure 21 Ideal Polar Diagram

4.9 Cell Size

An important parameter in providing a radio link to cover the last Kilometre is that of cell size, or put another way the ‘Link Budget’ associated with the link between the hub or node and the meter in the domestic or commercial site. The cell size must be large enough so that sufficient sites are covered by a node (traditionally the cost of a node is much higher than the cost of the installation of transponders in the customers site). Conversely the cell site should not be too large so that the node must handle large amounts of data as this may lead to data collisions or over loading of the path back to the utilities main office, both of which may cause loss of data.

As mentioned above the cell size is governed by the link budget. The link budget is made up by considering the following factors.

- The allowable transmitted power.
- Transmit and receive antennas gain (a measure of how well the antenna launches the radio signal into the air or captures a signal).
- The sensitivity of the receiver in the presence of noise (a measure of how well the receiver can recover the information modulated on the RF carrier).
- The attenuation of the radio signal between the two antennas.

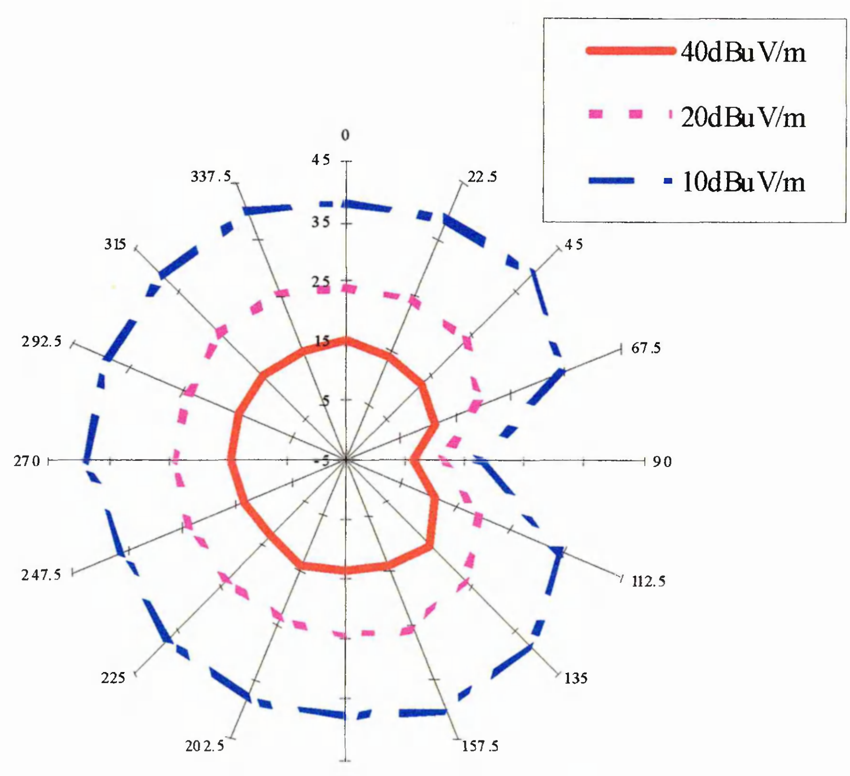


Figure 22 Distorted Polar Diagram

The points listed above are well understood and reasonably predictable with the exception of the attenuation between the two antennas. This will be dependent on the path or paths the radio waves take.

In free space the radio signal travels straight from the transmit antenna to the receive antenna. The transmission loss in free space can be derived [8] and is shown in equation 17 or more usefully in equation 18.

$$Loss_{fs} = \text{Power radiated/Power received} = (4\pi r/\pi)^2 \quad \ldots\ldots\ldots\ldots \quad 17$$

where r = distance from radiating antenna

λ = wavelength of the RF signal

or

$$Loss_{fs}\ (dB) = 32.44 + 20 \log fm + 20 \log D_{km}\ dB \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 18$$

where fm = frequency in Megahertz

D_{km} = distance in kilometres

The free space model can only be applied to the last Kilometre problem to give a crude estimate of the path loss, as the propagation mode is usually LOS or perhaps ground wave. The simplest model to consider in this case consists of two paths or rays, one directly between transmit and receive antennas and the other path from the transmit antenna to some reflective surface (for example the earth) and then to the receive antenna. The length of each path will directly affect the amplitude of the signal received, as will the reflectivity of the reflecting surface, and the reflected path will also determine the delay the signal experiences in that path compared with the direct path. The delays are almost certain to be different and will cause constructive and destructive interference at the receive antenna. If the time difference between the delays in each path is a significant fraction of the symbol period in a digital modulation scheme then Inter Symbol Interference may also occur.

4.10 Propagation over the last Kilometre

The 'last Kilometre' refers to the connection between the last substation, telephone exchange or distribution box and the customer premises. The customers may be commercial, industrial or residential and the residential sites are by far the most numerous; the various last Kilometre connections have been discussed in chapter 2.

Radio propagation over the last Kilometre is split into 3 main categories dependant on the environment the radio signal has to transverse. The environmental categories are Rural (Open), Suburban and Urban.

There are many prediction models for all types of radio propagation but they all tend to ignore the least probable propagation paths during the prediction process to make the calculations easier but with little loss in accuracy. The idea of using prediction models is to achieve maximum range or minimise the number of base stations or nodes while ensuring an adequate Quality of Service (QoS). The classification of the environment, including the average height of buildings, the amount and type of vegetation, and the size of hills and valleys, is important in predicting the coverage of for example a base station. Note that Shadows occur behind large obstructions and are caused by signals being blocked by those large objects, as shown in figure 23.

The propagation path between transmitter and receiver in an urban environment can be difficult to predict especially if one or both of the antennas is below the roof tops. The path will then be non line of sight (NLOS) and will entail reflections where the radio wave is reflected from buildings, street furniture such as street lights and junction boxes, diffracted by the sharp corners of buildings and scattered by the leaves of trees and bushes or the elements of walls and such like. A phenomena called ducting may occur where a radio wave is reflected from the buildings in such a way the signal is guided or ducted along a path that it would not usually take, an example of this may be a curved street where the transmitter is sending a signal into one end of the street and it may be easily received at the other end even though it is not a line of sight path.

These affects are dependant on the size of the objects causing the effect and the wavelength λ of the propagating wave.

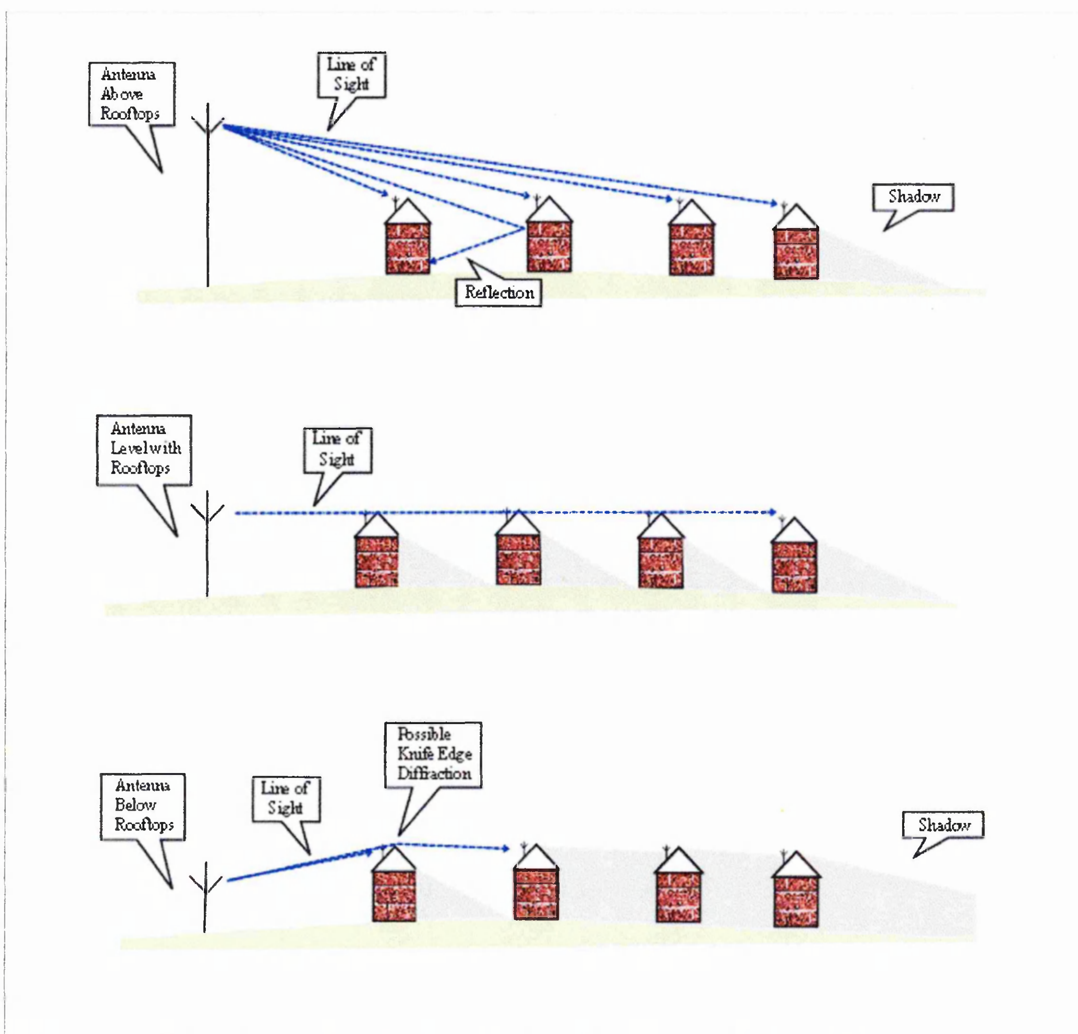


Figure 23 Effect of Antenna Height on Coverage

The radio signal will travel by several different paths between the transmitter and receiver and this is given the collective name 'multipath'. The lengths of the paths will be different so the signal captured by the antenna will be a composite signal made up of constructive phase additions and destructive phase additions as well as several images of the signal arriving at different times and with different amplitudes.

If either or both of the terminals is in motion then the multipath effects vary with the movement giving rise to rapid fluctuations in signal strength called fading. Even if both terminals are static it is likely that some of the obstructions in the propagation path are mobile especially in an urban environment. The main ways to combat fading are to use antenna diversity where 2 or more antennas are connected to the same receiver which selects the strongest signal, or to apply a fading margin where the radio system is specified with sensitivity that is not at the limit of reception. The fade margin which can be anywhere from 6 to 30dB is used to maintain the quality of service.

When several signals or echoes arrive at the receiver at different times this is called Delay Spread. When received and demodulated the spreading or smearing of the recovered data bits in the receiver may cause inter-symbol interference (ISI) which will limit the maximum data rate of the system. This inter-symbol interference is where the decision making section of the demodulator must choose if the incoming data bit is a one or a zero and the delay images of the signal make this decision difficult. The transmission data rate must be less than the coherence bandwidth of the receiver. A rule of thumb for cellular radio is rural / open < 0.2uS delay spread; suburban = 0.5uS delay spread; urban = 3uS delay spread. Delay spread can be combated with adaptive equalisation where the delayed and attenuated images are subtracted from the received signal, but the equaliser must be adaptive as the delays change as objects in the environment move.

The propagation path may also be subject to frequency selective fading. This is usually only evident in broadband signals and is where some frequencies of the signal are attenuated more that the rest of the signal. This may be due to scattering effects where the propagation paths are different for different parts of the broadband signal. Complex modulation schemes such as Spread Spectrum with high processing gain or Orthogonal Frequency Division Multiplexing (OFDM) can be used to mitigate the effects of selective fading with increased complexity in the terminals and possibly reduced range.

The propagation paths in urban, suburban and rural environments have been the study of many engineers and the subject of many papers. Okumura et al (September 1968) *Field Strength and its Variability in VHF and UHF Land-Mobile Radio Service*, Review of Electrical Communications Laboratory Volume 16, Number 9-10 [9], Hata M, (August 1980) *Empirical Formula for Propagation Loss in Land-Mobile Radio Services*, IEEE Transactions Vehicular Tech. Volume VT-29 ([11], have made notable contributions. Large advances in propagation prediction and cell coverage using computer tools have been made over the last few years driven mostly by the mobile telephone market. These software based prediction tools mostly use a combination of empirical measurement, previously calculated models and ray tracing techniques. They need as much information as possible in the form of maps, details of terrain such as heights of hills, buildings, trees and bushes, antenna heights, radio specifications and predictions of the probable radio environment in the form of interference and noise levels.

4.11 Link Budget

The discussion up to now has assumed that both transmit and receiving stations and their respective antennas have been fixed and for an Automatic meter reading (AMR) system this may indeed be the case. Once one end of the radio link is allowed to move such as when a meter reader is walking or driving a route the propagation path becomes even more difficult to model accurately and some assumptions have to be used to account for the movement. This is due to the fact that for each position of the moving antenna there are various propagation paths that cause additive or destructive combinations of signals. The Rayleigh distribution gives a good approximation to this fading environment [9]. The Rayleigh distribution is used to increase the loss over the radio channel as part of the link budget thereby effectively reducing the range over which the radio link will work reliably.

A link budget is a simplified mathematical description of the path from a transmitter to a receiver. The basic expression is shown in equation 19.

$$Ra = Tx + Gtx - PL + Grx \quad \ldots\ldots\ldots\ldots \quad 19$$

Where

Ra = Received power at the receiver antenna port

Tx = Transmitter power

Gtx = Transmit antenna gain

PL = Path loss between antennas

Grx = Receive antenna gain

For reliable communications the result found in equation 19 must be greater than the receiver's signal to noise ratio for a given bit error rate (BER). For example a transmitter generates 1 watt or +30dBm of transmit power. The transmit antenna is a ½ wave dipole with a gain of 5dB, the path loss between antennas = 97.7dB (gain = - 97.7dB), the receive antenna gain for a quarter wave mono-pole antenna is +3dB.

Thus the link budget = 30dB + 5dB - 97.7dB + 3dB = -59.7dB

The sensitivity of a data receiver will depend on the data rate, the receive frequency, modulation type the cost, complexity and efficiency of the demodulator and many other factors but is likely to be in the order of –90dBm. The link budget shows a margin of 30dB and that is adequate to allow for fading due to motion of the transmitter or receiver.

Another factor to take into account is that the not all of the signal may be faded or attenuated by the same amount. The same mechanism where different frequencies within the RF signal are reflected slightly differently causing different path lengths that may combine destructively where the other parts of the signal combine constructively. This is called selective fading and is more prominent inside buildings or other small spaces. New modulation techniques made possible by the high integration now possible in integrated circuits such as Orthogonal Frequency Division Multiplexing (OFDM) can be used to combat the effects of selective fading.

4.12 Summary

Chapter 4 has described the theory of a propagating radio wave using Maxwell's equations and described the modes that a propagating radio wave may take. Chapter 4 also described the various regulatory bodies and how they fit together. Polar diagram and link budgets were introduced as were system protocols and modulation types. Chapter 5 will describe the 2 sets of trials undertaken for this thesis. First the power line carrier trials of a low frequency alarm system to alert occupiers of domestic and industrial sites in a public information zone. The second set of trials of the 2 way radio automated meter reading system as installed in Goole West Yorkshire.

Chapter 5 Experimental trials of PLC and Radio Systems

Introduction

Chapter 3 covered power line carrier and chapter 4 on radio propagation have laid the ground work for the experimental work presented in this chapter. Two areas of experimentation are explained, a power line carrier public alarm system and a two way radio system capable of reading electricity meters in domestic and light commercial customer sites in Goole, West Yorkshire. The experimental work is presented with the power line carrier trials first and then the radio link experiments. In both sets of trials initial tests were carried out to establish the viability of the system prior to installation in customer sites. In the case of the power line system such a public trial has yet to take place.

5.1 Nimbus Power Line Technology Public Alarm System

The Nimbus Power Line Technology Public Alarm System, as shown in figure 24, is a practical application of a low frequency power line carrier system.

This system is designed to give members of the public warning of an incident in the area around a Control of Major Accident Hazards site (COMAH). A COMAH site is where there is a hazardous operation or storage facility, for example a chemical factory or oil refinery. The area surrounding such a site is called a Public Information Zone or PIZ. These zones are at present 3 kilometres in radius but that may be extended to 10 kilometres in the near future.

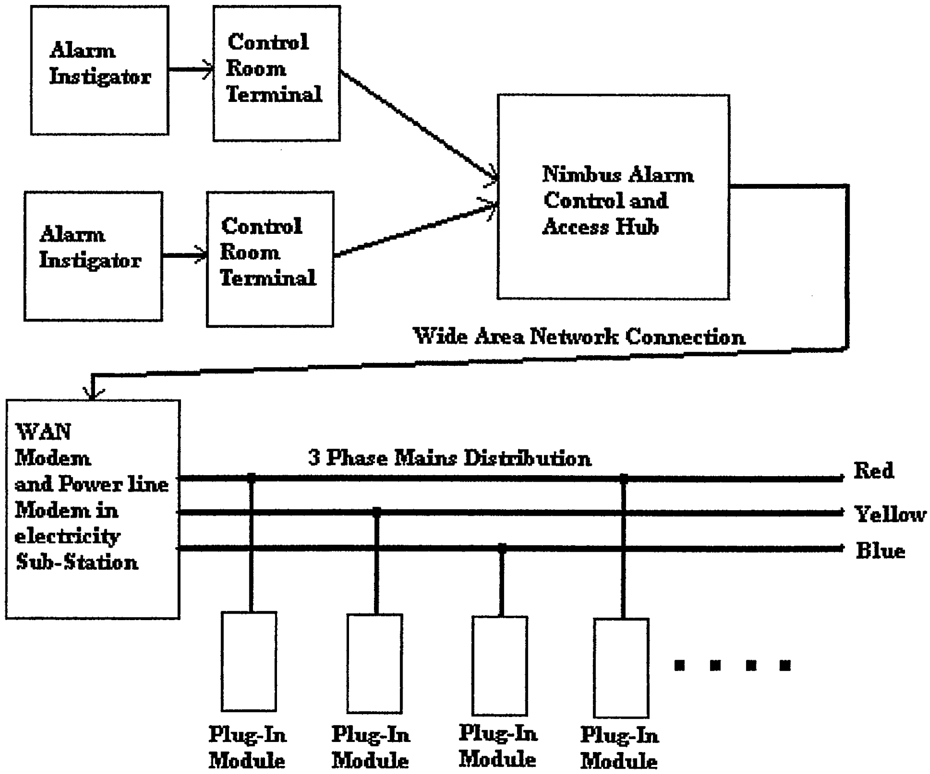


Figure 24 Nimbus System Block Diagram

The site operator has a duty to the public within the Public Information Zone (PIZ) that is within a 3 kilometre radius of the site, to warn of any incident that may harm them or their property. Presently this is achieved in two ways, by siren or by a computerised telephone dial up system where each telephone within the PIZ is called in turn and the warning given. Both of these systems have inherent draw backs, such as the time taken to dial all of the telephones and the wind direction for the siren.

The Nimbus system is a broadcast system where all of the selected homes in the PIZ will be informed at the same time. This is achieved by mounting a power line modem in each electricity substation that supplies power to premises in the PIZ. Each power line modem is fed information from the control room of the COMAH site when an incident is in progress. The information from the control room is sent to the Nimbus server which then routes this information as appropriate to the relevant power line modems. This information may be sent to each power line modem by any means available such as PSTN network or private telephone lines or radio link such as mobile phone. The power line modem then sends command signals down the power lines to the Plug-In modules mounted in each home / office. The command signals include the addresses of the Plug-In modules that need to be triggered.

The addresses of the Plug-In modules allow any or all Plug-In modules to be triggered when required. This is to allow only those Plug-In modules that are in the predicted 'plume' or other danger area to be triggered so as to minimise the disruption and anxiety of the other home owner's within the COMAH PIZ who are in no danger.

The Plug-In module is shown in figure 25 is designed to mount in any standard 3 pin 13A mains socket in a house or office. It will sit powered up and 'on watch' (green Screen) waiting for an alarm/ alert. On receipt of a valid trigger message the screen will usually go to amber and following a siren an alert message will be spoken and displayed on the screen. The next generation of Plug-In module will also feature a bright white LED pointing to the ceiling and flashing. These alert messages will be updated approximately every 10 minutes until the alert is over or the situation deteriorates. If the situation does deteriorate incoming message from the COMAH control room causes the screen to go to red and following a new siren the alarm message is spoken and displayed. These 'red' alarm messages tell the observer to do something such as evacuate to a safe area such as the town hall school.

Figure 25 Nimbus Plug-In module installed in a home

5.1.1 Report on Trial of Nimbus System carried out at Open University

The aim of this trial of the Nimbus system was to test the system over longer transmissions distances than the in house trials and in an expected hostile environment with many computers, fluorescent lights and air conditioning units running. The Open University building at Manchester is a new building, less than 3 years old, with modern wiring. There was some question on which mains sockets were connected to which phase which has not been fully resolved.

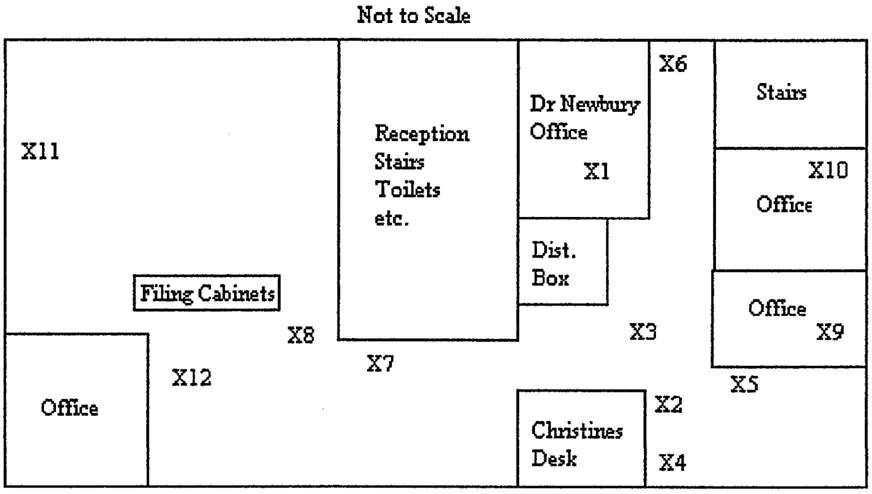
The Nimbus system consists of a laptop or PC running the Nimbus front end software connected to some type of transmission unit linked via a GPRS / Mobile telephone. The GPRS / mobile telephone provides the Wide Area Network (WAN) connection to the Utility sub station unit that forwards the message to the Plug-In modules. At the other end of the system are the Nimbus Plug-In modules that react to the message with a screen display including colour change, an audible alarm and a spoken message. Messages from the COMAH control room are injected on to the mains in the sub station transmission unit using an ST7538 PLC modem on a demo board. The trial was conducted using a bare ST demo board connected to the laptop via a simple RS232 link. This setup made it easy to send repeated messages quickly.

Four Nimbus Plug-In modules where used during the trial. Two Plug-Ins have the capacitor C11 on ST Demo Board at 33nF, Appendix 5 Figure A5.3, and the other two Plug-Ins have C11 set to 68nF as suggested by Mr Cantone of ST (personal communication).

These modifications should increase the sensitivity of the Plug-In module. The ST Demo Boards also have 68nF capacitors in the C11 position.

A monitoring system was constructed to measure the noise and possible performance of the Nimbus system and this monitoring system is detailed in Appendix 1.

A floor plan of the 3rd floor of the Open University building including Dr J Newbury's office is shown in figure 26.



Floor Plan of 3rd Floor at Open University Building Manchester
(X marks Plug sockets where Nimbus Plug-In modules tested)

Figure 26 Layout of Open University Test Site

5.1.2 <u>Trial Details</u>

Test number one was conducted in Dr Newbury's office as shown in figure 27. The full Nimbus system was connected to mains socket X1 and the Plug-In modules distributed around the office.

The transmitted signal woke all four Plug-In modules.

Figure 27 Mr P Burns demonstrating the Nimbus software to Dr Newbury

The Nimbus Transmission system was then substituted for the ST Demo board plugged into X1 and the test repeated. The transmitted signal woke all four Plug-In modules. An oscilloscope was used to monitor the signal and noise seen on the power line during the trials as shown in figure 28, and the noise captured during the trial is shown in figure 29.

Three Plug-In modules where then moved to the other reception sites and the results in table 2 were gathered. Note that Plug-In number 4 stayed in Dr Newbury's room.

X position on floor plan	Plug-In 1	Plug-In 2	Plug-In 3	Plug-In 4
X1 (in Dr Newbury's room) Full Nimbus system!	√	√	√	√
X1 (in Dr Newbury's room) ST Demo Board	√	√	√	√
X2 Near Christine's Desk	no	no	no	√
X3 in middle of room	√	½ √	√	√
X3 in middle of room Repeated	√	√	√	√
X4 By the wall	no	no	no	√
X5 Next to photo copier	no	no	no	√
X5 Next to photo copier Repeated	no	no	no	√
X6 By the Shredder	√	√	√	√
X7 by the wall	√	√	no	√
X8 by the water cooler	no	no	no	√
X9 in middle of office	no	no	no	√
X10 by window in another office	no	no	no	√
X11 by 2nd shredder in large room	no	no	no	√
X11 repeated in same place but in different plug	no	no	no	no
X12 by assistant Director's office	no	no	no	no
Connected ST Demo board at X6, Plug-In X8	no	no	no	no
ST Demo at X6, Plug-In modules in X1	√	√	√	√
ST Demo at X6, Plug-In modules in X9	√	√	√	√
ST Demo at X6, Plug-In modules in X10	√	½ √	√	√
ST Demo at X6, Plug-In modules in X10	√	√	√	√
ST Demo at X6, Plug-In modules in Coffee Room below Dr Newbury's Office	no	no	no	no

Table 2 Test positions at Open University test site as detailed in Figure 26

Note that ½ √ meant the screen changed colour but the message did not display. This proved to be a software bug in the Plug-In modules.

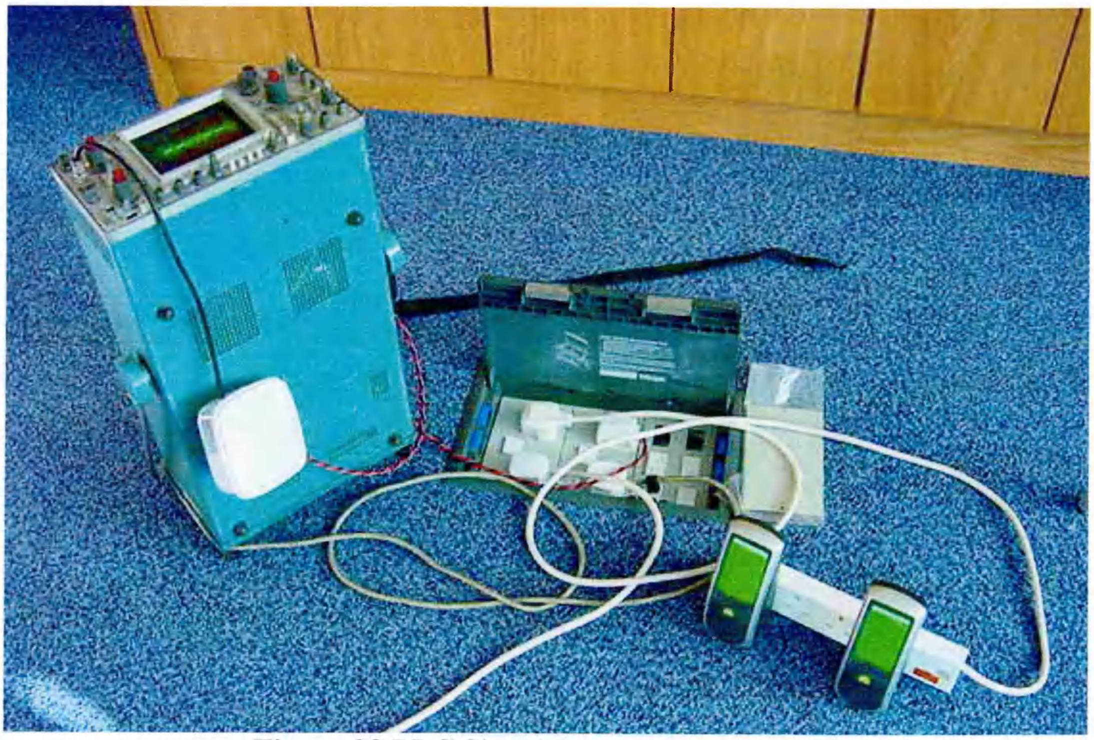


Figure 28 PLC Signal Reception test set up

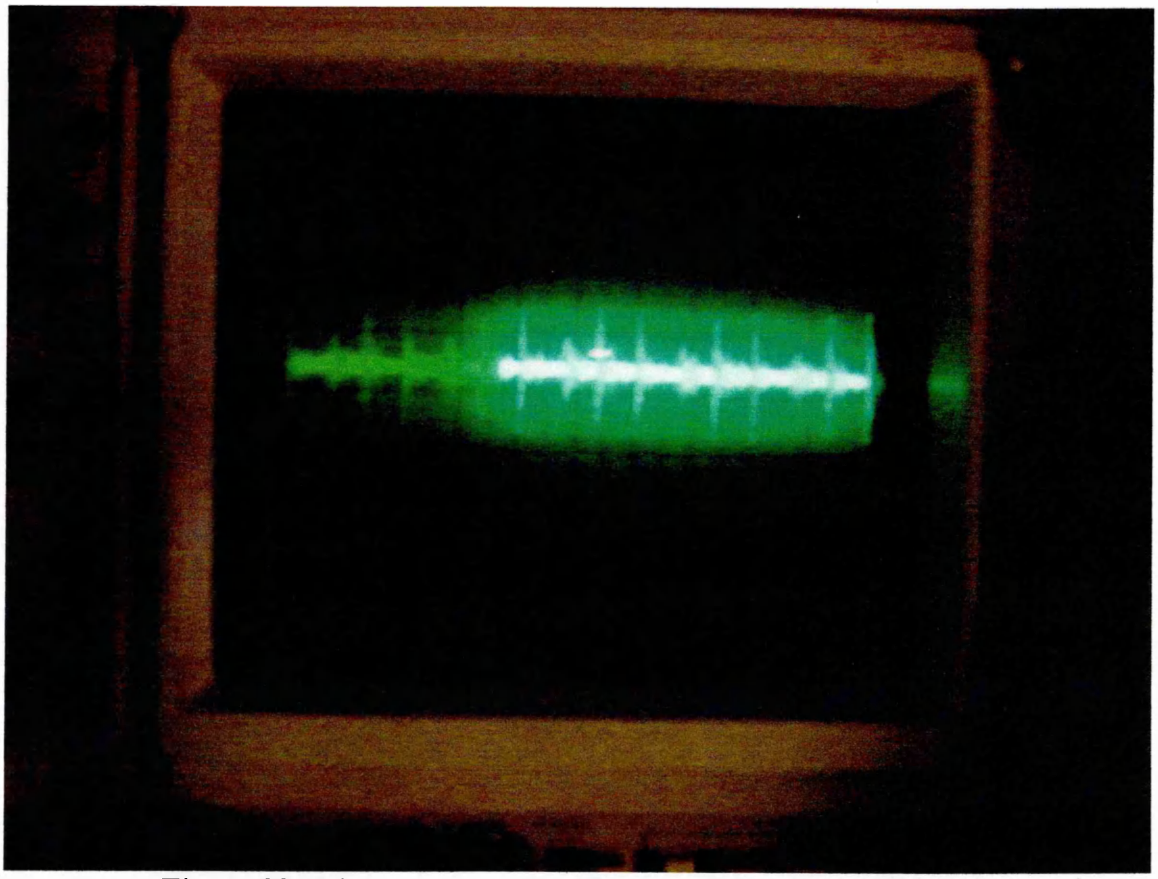


Figure 29 Noise as seen on Oscilloscope (0.1 volt per division)

5.1.3 Subsequent Tests at Nimbus Offices

Some further trials were conducted at the Nimbus Offices to investigate the perceived poor performance. These involved comparing the signal levels between the two ST Demo boards. Note all circuit references refer to the circuits in Appendix 5 figure A5.3 and in ST Microelectronics application note AN1714 [16].

The ST Demo board in the Nimbus transmission system injects a signal between 2 and 4 times larger than the ST Demo board used in the Open University trials, also the level control potentiometer R12 has no effect when adjusted (on the ST Demo board with the small output).

When the junction of L4 and C11 (see Appendix 5 figure A5.3) was probed with an oscilloscope on the Demo board with the larger transmitted signal (at 132,5kHz) the peak to peak 50Hz voltage was approximately 10v whereas on the other (Low 132.5 kHz signal) Demo board the peak to peak 50Hz voltage was greater than 300v. It appears there is a fault on the Demo board with the high 50 Hz voltage. Simple DC comparison tests between the two Demo Boards failed to show the faulty part.

It was decided to send this 'faulty' board (with the 300v signal) back to ST Microelectronics in Italy for analysis and repair.

5.2 Conclusions

These trials while useful in causing the team to investigate the performance of the ST7538 Demo Boards did not settle the concerns of the Nimbus team of what sort of range may be achieved when conducting a live trial. The confusion as to which sockets are on which phase will be sorted out prior to the next trial, and the best Demo board will be chosen so as to minimise the variables within the trial.

5.3 Trial of Nimbus system at the NEDL Kepier Site

The aim of this Trial of the Nimbus system was three fold. Firstly, to test the range and performance of a number of Nimbus generational and optional systems on a live 230v 3 phase quiescent environment under virtual no load and minimal 'noise' conditions whilst being supplied by an overhead line 11kV transformer. Secondly, to specifically transmit over a distance sometimes referred to as the 'last kilometre'; though in this instance the measured distance is 550metres, on a typical low voltage UK urban domestic power line distribution network. Thirdly, to monitor and record transmission signal values at the injection point and remote or far end of this circuit.

5.4 The Trial Site

The venue provided by CE Electric UK for the trials was the Fault Management Training System which is a controllable environment three phase domestic low voltage distribution network typical of those found in the UK which is used for in-service training as shown in figure 30, figure 31 and figure 32.

Figure 30 Kepier Training Site

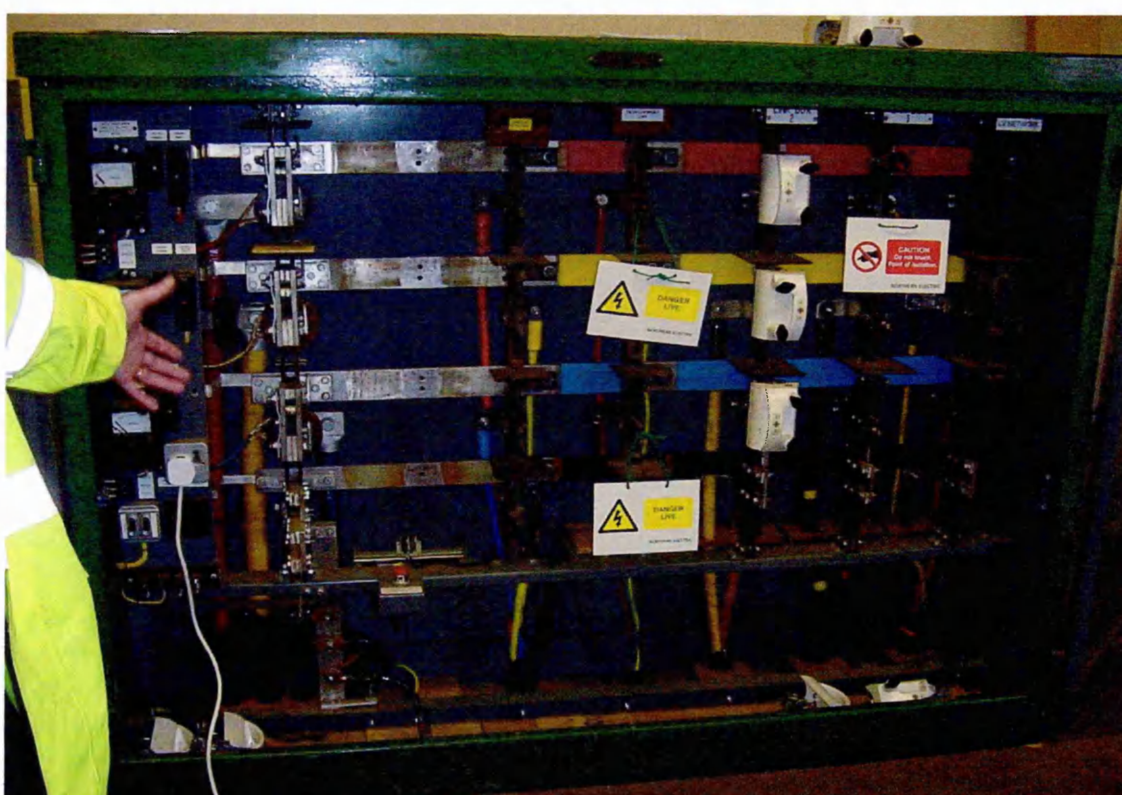


Figure 31 Electricity sub-station distribution panel

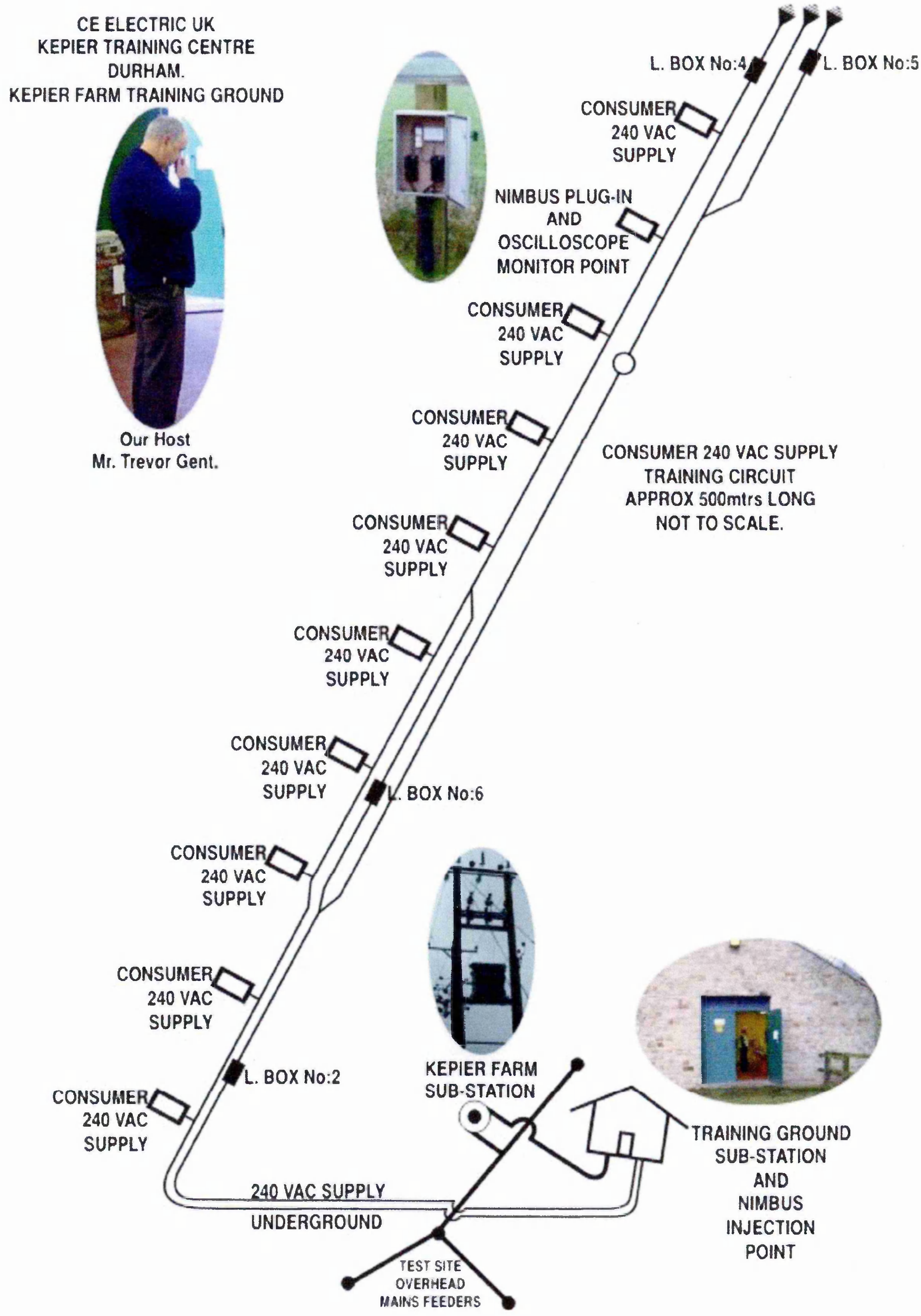


Figure 32 Kepier Trial Site Block Diagram

5.4 Trial Equipment

5.4.1 Nimbus Mk1

The Nimbus Mk1 system comprises two major essential elements namely two laptop computers with Nimbus proprietary representative GUI's accompanied by two analogue Power Line Modems (PLM) (shown in figure 33) utilising National Semiconductor chipsets.

Originally developed some five years ago by Mr Paul Burns and partners as a tool to demonstrate 'concept of idea' for market evaluation purposes this system, though operational, can for all commercial purposes be regarded as obsolescent as indeed the chip sets are. However, though not meeting EN50065 specification because of continuous carrier operation, the amplitude of the transmissions is nevertheless broadly in line with the legal requirements as laid down in EN50065.

Figure 33 Nimbus Mk1 Systems

5.4.2 Nimbus Mk2

The Nimbus Mk2 system comprises three essential elements shown in figure 34. The first element is the proprietary Nimbus WAN software which is installed in a desktop or laptop and is commanded by a trained operator who configures and selects the area to be alerted. Once the alarm area is selected on the laptop by the operator the laptop can transmit a standard message string via the WAN Link to the Transceiver/ Decoder unit usually fitted in a Utility electricity substation. This WAN link is presently achieved via GPRS/Mobile/SMS telecom to the Transceiver/Decoder unit with an appropriate SIMMs for the TMobile commercial network. The second element, the Transceiver / Decoder unit, uses a matching GPRS/Mobile/SMS data link receiver, again utilising an appropriate SIMM for the TMobile commercial network to link back to the operator. The Transceiver / Decoder unit uses an on the fly Rabbit microprocessor development board which translates the data form the WAN link for onwards communication to the ST7538 PLC modem on an STM board which places / retrieves the message string on the mains power line for transmission. The third element is the Nimbus Plug-In module that receives the message string and subsequently displays the message and provides the alert/alarm cues to the 'consumer' at the House Access Point (HAP) as shown in figure 35.

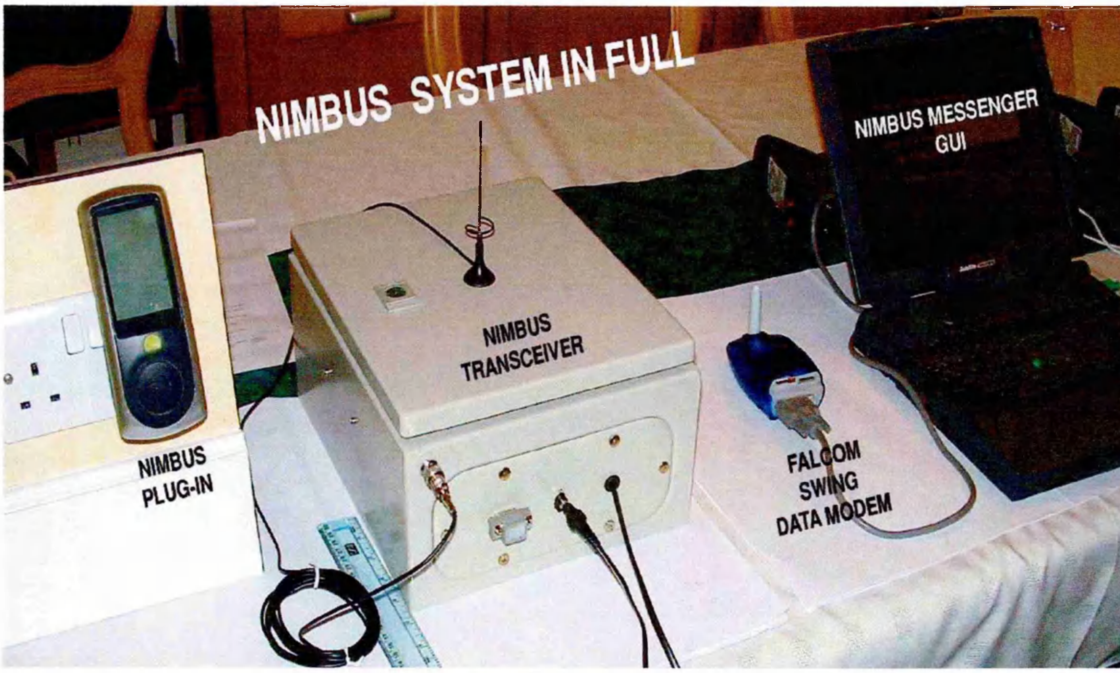


Figure 34 The Nimbus Mk2 System

5.4.3 Nimbus Plug-Ins.

Two Nimbus Plug-In modules were used during these trials, Build # PI-1000007 unmodified and used at the 'top' or injection point of the transmission system as a monitor. Build# PI-1000011 modified by changing L4 (for explanation see Appendix 5 Figure A5.3) from 22uH to 10uH, and used as representative of a 'consumer' Plug-In alert device such as installed beyond the HAP somewhere inside the premises in future. This was installed at the 'bottom' or remote end of the distribution end of the transmission network as shown in figure32.

5.4.4 ST Microelectronics ST7538P Demonstration Boards

Two ST7538P-1 demonstration boards, as shown in figure 36, were used; one of which is incorporated in the Nimbus transceiver unit with an RS232 direct bypass link to STM board access circuit. This RS232 bypass permits direct string transmissions of from laptop to Nimbus/STM board and then to Nimbus Plug-In without using the public telecoms network. Both STM boards are modified as recommended by Mr. G. Cantone ST

Microelectronics and for the current tests both used their original software and firmware versions.

Figure 35 Nimbus Plug-In (Build#100011) installed in the test HAP

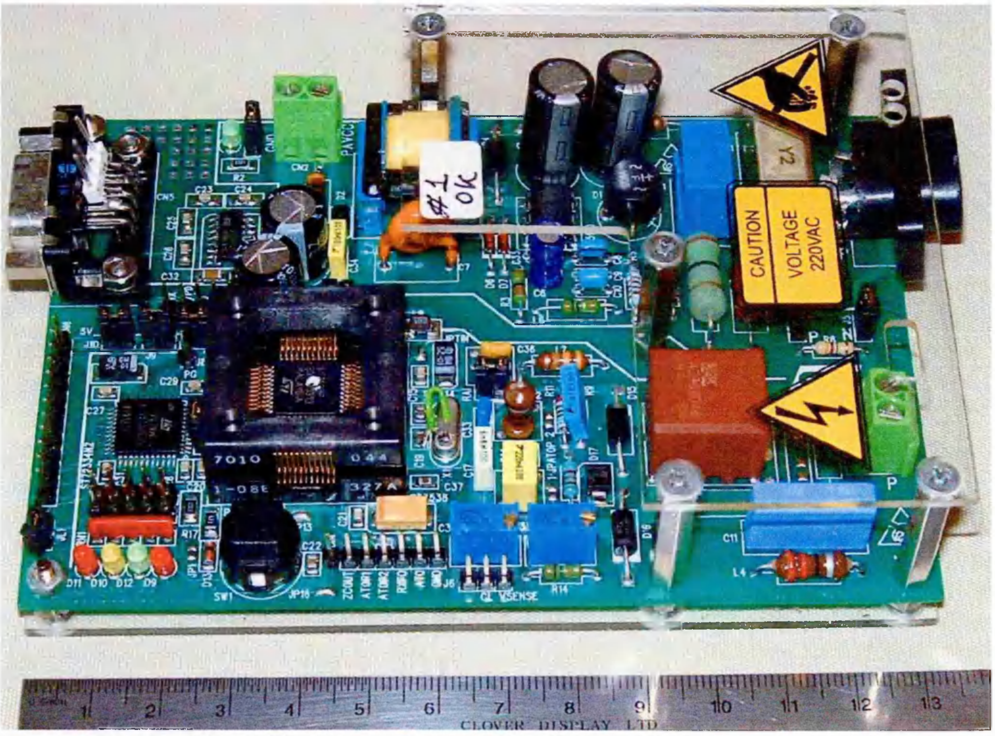


Figure 36 Modified ST Microelectronics ST7539P-1 Demonstration board

5.4.5 Nimbus Monitoring System.

A monitoring system including a line/signal monitoring Telequipment DM64 oscilloscope was constructed to measure the noise and the performance of the Nimbus system and this monitoring system is detailed in Appendix 1.

5.5 Test Configurations.

There are a number of optional configurations which can be used for field test purposes. Most test the functionality of the Nimbus systems; however, some act to verify the functionality of individual modules or as a 'step into' facility to expedite testing.

5.5.1 Signal Reception Test Configuration 'A' Nimbus Mk1:

It was intended to initially assess the Low voltage (LV) system, with 230 volt power applied, for local noise by means of the oscilloscope. Then using the oscilloscope in conjunction with the Nimbus Mk1 to identify and confirm the correct phase upon which to carry out the remainder of the tests and to initially ascertain carrier degradation, if any, over the circuit distance of 550metres. This Nimbus Mk1 system transmits a continuous carrier at approximately 153 kHz. Whilst not entirely meeting the EN50065 specification this power line modem nevertheless permits the viewing of the received signal at the other end of the distribution system some 550 metres away using a coupling circuit and oscilloscope as shown in Appendix 1. This also provides essential confirmation that both ends of the test site circuit are connected to the same blue phase and that further test signal transmissions can take place.

Figure 37 Nimbus Mk1 PLM Transmitting in Training Ground Sub-Station

The Nimbus Mk1 Modem as shown in Figure 37 at the Kepier Training Ground Sub-Station was connected to the blue phase and driven by a laptop running Nimbus Mk1 propriety GUI COMAH software. At the HAP receiving end a Nimbus Mk1 modem was connected to another laptop running a propriety Nimbus program which represented a facsimile of the intended Plug-In. The oscilloscope was connected to the same phase at the HAP and measurements made of the received signal. This equipment was set up in the rear of the Nimbus vehicle as shown in figure 38 and figure 39.

Figure 38 Nimbus Mk1 PLM Receiver Set Up in Nimbus vehicle

Figure 39 Vehicle with Nimbus Mk1 test system connected to HAP

5.5.2 Test numbers 1 to 5

The Nimbus mark 1 system was used to test the transmission path as it was easier to see a constant sine wave at the HAP than to look for short pulses of information on the oscilloscope screen. Once it was confirm that the HAP was on the same phase the Nimbus Mark 1 system was tested 10 times from the Training Ground Sub Station to the HAP. All messages were received 100% successfully.

The signal injected by the Nimbus mark 1 system at the Training Ground Sub Station as measured on the oscilloscope, using the test system detailed in Appendix 1, was 1.25 volts p-p (peak to peak) and the received signal at the HAP approximately 550 metres away was 0.75 volts p-p using the same test set up. This showed a signal loss of -4.4dB over the 550 metres of buried 3 phase 240v mains distribution cable. Figure 40 shows the PLM with the 1.25 volt p-p carrier wave on the oscilloscope screen.

Figure 40 DM 64 Oscilloscope with Transmit signal from the Nimbus Mk1 PLM

5.5.3 Signal Reception Test Configuration 'B'

This configuration requires the use of a modified Nimbus Mk2 system which involves the use of STM front-end test software transmitting a binary/ASCII Nimbus message string taken at random from a library of the current 51 messages stored within every Plug-In and transmitted to the Nimbus transceiver using the RS232 direct bypass link to the internal STM board access circuit. In other words the data signal is directly injected into the ST Microsystems Power Line Modem (PLM) bypassing the Nimbus WAN as shown in figure 41.

For the trial this configuration included the use of two Nimbus Plug-In modules, one (unmodified) at the top of the circuit to act as a local monitor and a second (modified) at the bottom of the circuit to simulate reception of the messages at the 'consumer' or HAP end.

This test used the ST M board Control Register settings listed in table 3.

Carrier = 132.5 kHz	600 baud	Deviation = 1
Interface = Synchronous	Watchdog = off	Time out = 1S
Detect method = Carrier	Detect time = 1mS	Zero crossing = disabled
O/P clock = 4 MHz	Packet = Disabled	Packet rate = MCLK/64
Packet length = 9 bit	Sensitivity = Normal	Pre-Filter = off

Table 3 ST Demo Board Settings

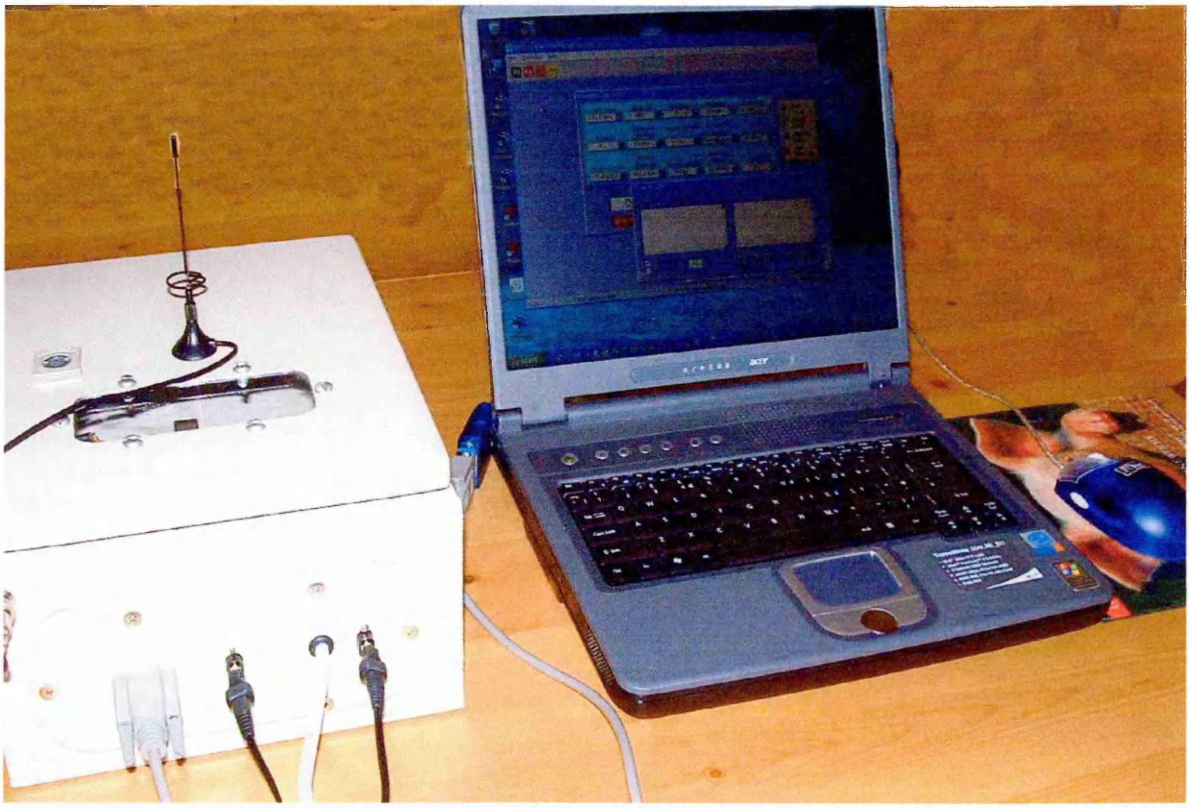


Figure 41 Configuration 'B' Laptop plus Sub-station unit

The Nimbus Mk2 system was again tested 5 times. All signals were received correctly by both the monitoring Nimbus Plug-In at the Sub-Station and by the Plug-In installed at the HAP. All alert/alarm outputs from the Plug-in modules were sounded or spoken or displayed on the screen and colour cued correctly. Note that messages have a green background (such messages as 'All Clear' or 'Return to Your Homes') while warning messages have an orange background (such messages as 'Alert Gas Release') while the rest of the messages have a red background (such messages as 'You Should Evacuate to ….')

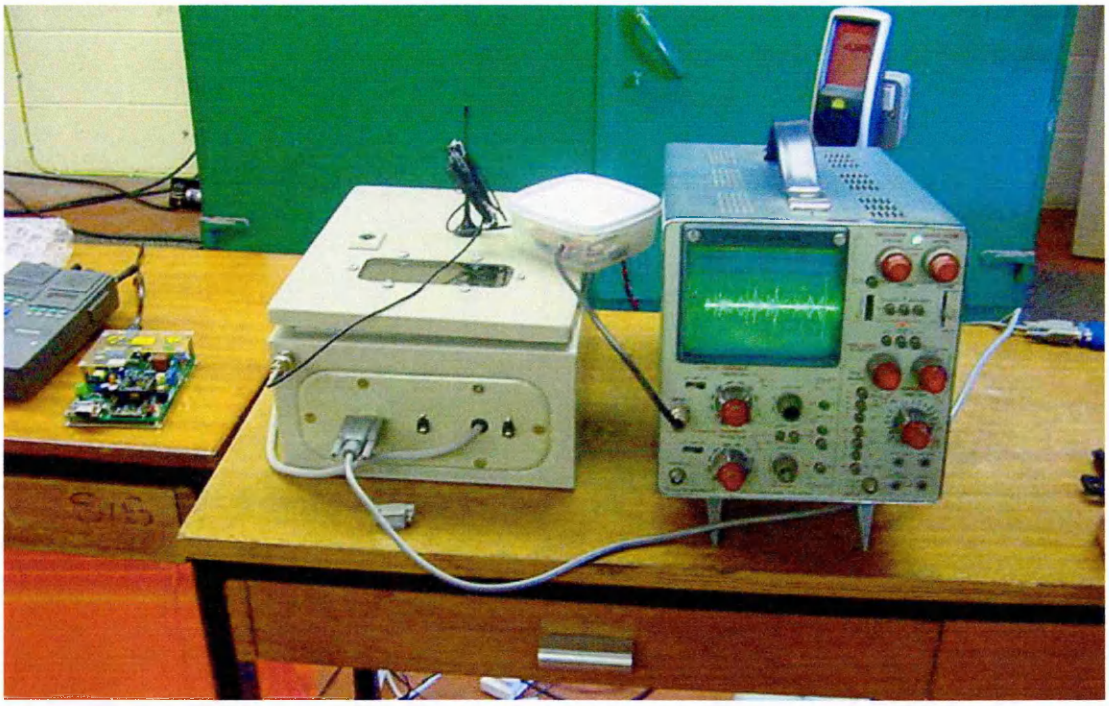


Figure 42 Nimbus Mk2 Transmittter; note oscilloscope showing noise

5.5.4 Signal Reception Test Configuration 'C'

This full system top to bottom configuration as shown in figure 42 utilises the Nimbus Mk2 WAN coupled by the RS232 to a Falcom SIMM module on the TMobile network. This in turn communicates over the public SMS network to an A2D SIMM module; to the 'on the fly' MCU; to the STM board and thence down the power line to the Nimbus Plug-Ins at the HAP.

Three full tests were carried out covering the range of emergency messages likely to be used on the live customer trials. All signals were received correctly by both the monitoring Nimbus Plug-In at the Sub-Station and by the Plug-In installed at the HAP.
The Nimbus Mk2 system clearly meets the EN50065 specification when transmitting over a power distribution system as the ST7538 FSK Power Line Modem IC (that is the heart of the Nimbus system) is compliant with this standard [16] [17], see also Appendix 5. The signal injected at the Kepier Training Ground Sub-Station was measured using the test setup as detailed in Appendix 1. The signal was measured on the oscilloscope at 1.4 volts p-p. The received signal was measured at 0.8 volts peak to peak, thus the loss over the 550 metres between the Kepier Training Ground Sub-Station and the HAP was approximately -4.9dB.

5.6 Trials Conclusions and Recommendations

5.6.1. Given that the Kepier Training Ground Facility had no service applied loads at any of the House Access Points and given that the only noise induced was that which was induced by the 11kV to 415 volt transformer or pickup from the surrounding environment the Kepier test circuit could be considered to have ideal parameters and as a consequence the Nimbus Mk2 system performed as expected. The correlation between the signal loss encountered by the Nimbus Mk1 system and the Nimbus Mk2 system demonstrated that the measurements made were completely consistent.

5.6.2 The ST Microelectronics Application Note AN1714 gives the transmit power from the EvalST7538P-1 power line modem as approximately 123.5dBμV as set by EN50065. The average receiver sensitivity of the EvalST7538P-1 power line modem in normal sensitivity mode is 66dBμV. The difference of 57.5dB is the margin which allows for noise and attenuation over live power distribution system. The loss of 4 – 5dB over 550 metres at the Kepier Training Ground Facility is unusually low and this can be attributed to the fact that the distribution system is unloaded.

5.6.3 The ST Microelectronics Application Note AN1714 suggests real-life attenuation over a similar distance of 10 – 15dB with an additional 10 – 20dB loss if the signal passes via a service panel at the HAP. Taking the maximums (15dB + 20dB) this still leaves 20dB margin for noise. This may be optimistic, however, a relevant consideration must also be that the transmission software used on this test, both Nimbus and STM contained no form of Forward Error Correction (FEC) or other algorithm for signal retrieval which would make the systems tested vulnerable to any form of noise however slight.

5.6.4 The focus of development work prior to the next trial will be to enhance the existing transmission software to meet all envisaged, or created, challenges. This will involve not only the production of revised code but the re-programming of all relevant parts of the Nimbus system especially to incorporate some form of Forward Error Correction FEC.

5.7 Introduction to Radio Trial at Goole Yorkshire

The aim of my thesis is to investigate ways of providing a communications links over the last kilometre to homes and small businesses. One main area of work has been the design and installation in conjunction with the Yorkshire Electricity Group of a 2500-point two-way radio electricity meter reading system centred at Goole in Yorkshire. One of the main requirements of this trial was to gather ½ hourly electricity meter readings from domestic dwellings and light industry. This would in conjunction with electricity suppliers pricing their electricity in ½ hourly slots allow consumers to choose when to buy electricity. This in turn would allow generators of electricity to price the electricity to smooth out the demand.

Two preliminary trials were conducted prior to the customer trial. The first trial was a simple feasibility study and this was followed by a technology trial. The technology trial site was chosen that offered good access to the node equipment and some customer sites that were members of the Yorkshire Electricity Group PLC Company. This site was found at Lindley near Huddersfield.

The customer trial site at Goole in Yorkshire was chosen as the area was relatively flat reducing any variations in propagation and coverage due elevation changes. There is a tall water tower in the centre of Goole and initially it was thought that a Node place at the top of this water tower may cover the complete town. It was quickly realised that problems with supplying mains power and access to the site along with the fact that this was not representative of many towns meant that the choice of Node sites was reduced to those that provided good access with good security for the equipment and an antenna mounting point that allowed coverage of the proposed cell. The Goole Town site also encompassed many types of buildings with the majority being in people's homes. During the trial period I gathered a large amount of experimental data including signal strengths, ranges, and propagation paths especially into various sites within the houses.

5.8 <u>The Yorkshire Electricity Group (YEG) project</u>

The Feasibility / Link Budget Trial was conducted to ensure that the radio link at 184MHz would give enough coverage to ensure an economic ratio between customer's electricity meters and data concentrating nodes. The trial consisted of setting up an un-modulated low power (1 watt) 184 MHz transmitter at a service centre and measuring the signal strength and noise floor at various distances from the service centre. The transmitter was connected to an end fed monopole antenna mounted at the height that the data concentrator's antennas would be likely to be mounted. The 'receiver' in this case was a spectrum analyser with low noise tuned front end amplifier to overcome the noise floor of the spectrum analyser. This utilised a commercial dipole antenna mounted on a wooden pole. No attempt was made at this time to assess the attenuation the signal would experience when penetrating a building.

The Technology Trial ensured that the various parts of the system would work together without spending too much time and money designing a system with inherent problems. The trial was conducted around a service centre with 66 domestic meter sites supplied by company employees that lived it the area as listed in table 6, page 109. Siemens S2AS electronic meters were connected in series with the existing electricity meters to compare readings. The trial was run for 4 weeks and the meter readings gathered on a laptop connected to a simple data concentrator, set up in the Utility's local service centre. The frequency of transmission was again 184MHz but this time modulated with Binary Phase Shift Keying (BPSK). BPSK is a modulation system where the phase of the transmitted signal when compared to a reference can take up one of two phases. Each phase represents either a one state or a zero state. A preamble and start byte are transmitted at the start of each packet of data and these tell the receiver the frequency and reference phase of the transmitter so that the receiver can successfully recover the data. The transmitter antenna was the same commercial dipole as used during the feasibility trial. The transceiver at the electricity meter was mounted in a Siemens case designed to fit over the electricity meter as shown in figure 47, the antenna at the Siemens meter was an externally mounted helical antenna tuned for 184MHz.

The Customer Trial was conducted at Goole and consisted of 2000+ customer premises including office type single phase commercial premises with a further small trial of commercial customer premises in the area around the headquarters of the Yorkshire Electricity Group in central Leeds. The commercial sites in Leeds all had 3 phase Calmu meters fitted and utilised a slightly different radio design with an external antenna and external power supply. The domestic meters were all Siemens S2AS electronic meters and the same Siemens case was utilized. The radio was redesigned for mass production and an internal antenna was design and manufactured. A similar signalling protocol to the Technical Trial was used but each data concentrator / node interrogated its specific group of electricity meters in turn according to a preset schedule.

Automatic Meter Reading (AMR) besides reducing billing costs to the Utility potentially offers considerable strategic benefit to Utilities by enabling them to offer enhanced customer service, network automation, performance monitoring and a platform for added value services such as multi-utility data collection, instant billing, and ultimately demand side management. Easy access meters cost between 50p and £1 (50c to $1 in USA) to read but difficult to read meters can cost up to £5 per read and commercial meters are read on a monthly basis. In Europe in the early 1990's there were estimated to be in excess of 350,000,000 meters that required reading and in the USA there were 235,000,000 meters with approximately 7,500,000 already fitted with AMR devices. An AMR device to fit to a meter costs on average £35 with £10 installation. The data concentrator will handle approximately 100 to 300 meter transponders and costs approximately £500 to £1000. The data concentrators connect to a host server that will cost in the region of £1,000,000 including software and communications suite.

A pilot project involving approximately 2,500 Yorkshire Electricity Group PLC customers in Goole Yorkshire has provided a mechanism for proving the technology of an

Automated Meter Reading system with full two way transmission, in addition the trial allowed preparation of system specifications, applications developments, and evaluation of the business case for a full scale roll out of a Radio Based AMR system. The AMR trial system implemented by RAMAR for Yorkshire Electricity Group PLC provided the data for two quarterly billing cycles for these customers, and the technology offered the capability for providing half-hourly readings anticipating emerging requirements of OFFER and the future demands from the customer in a de-regulated environment. The trial also allowed for transmission to each electricity meter to change billings rates or even cut off power in the event of non payment. Another benefit of the 2 way capability is to fit some transponders with battery backup, in the event of a power outage these transponders will signal power loss to the Node and thence to the Utility headquarters quickly giving the Utility up to date information as to the size of the problem.

5.8.1 Feasibility Study

Initially in replying to the tender offered by the Yorkshire Electricity Group some considerations had to be taken into account. Would a radio system provide the performance required by Yorkshire Electricity Group PLC and if so would it be cost effective? What frequency could be used to provide the communications channel and would the AMR system be the primary user of the communications channel or would the channel be shared, how much data would be transmitted and at what speed? A search of the regulations showed that a dedicated meter reading channel existed in the UK at 184MHz +/- 500kHz and this was split into 25kHz channels but that the 4 centre channels could be grouped together to be used as one 200kHz wide channel. This was laid down in European Radio Specification ETSI 300-220 as amended by the DTI RA TDS MPT1601 V2 August 1997.

I had, in conjunction with RAMAR Ltd, experience of transmitting meter reading data in the 184MHz channel and thus it was decided to use that frequency channel. Next would the system be cost effective, that is would the cost of installing the radio meter reading system divided by the number of meters read during the period of the trail add up to less than the manual reading of the meters. The coverage of a meter reading cell would be dictated by the range achieved by the radio system, Initial calculations shown in paragraph 5.8.2 suggested that the range of 750 metres would be viable.

5.8.2 Link Budget Calculations

For convenience in arriving at the "free space" range a simple flat earth model is used which takes into account simple multi-path reflections and the effect of the antenna heights [10]. *The actual free space range without the effect of the earth's surface would be much greater. In a practical urban environment the range will be affected by building and trees giving additional attenuation which is likely to be in the range of 10 to 50dB.*

Using the flat earth model the loss is given in equation 20 [19].

$$L_{db} = 117 + 40 \log d_m + 20 \log F - 20 \log h_t * h_r \qquad \text{.........................} \; 20$$

Where:

L_{db} is the path loss in dB.

d_m is the distance in miles.

F is frequency in MegaHertz

h_t is the height of the transmitter antenna in feet.

h_r is the height of the receiver antenna in feet.

For a electricity meter antenna height of 1.5m, the node (data concentrator) antenna height at 4m and a 750m range then path loss is given by equation 21.

$L_{db} = 117 + 40 \log(0.46605) + 20 \log(184) - 20 \log(13.124 * 4.9215)$ ………….21

Predicted Path loss L_{db} = 112.8 dB

184 MHz DFSK "Wake up" Receiver Sensitivity (mounted in Meter Transponder)							
Noise power = kTB = -174dBm / Hz							
NF= NF1 + (NF2 -1)/ G							
Where NF is overall noise figure, NF2 is noise figure of the first RF amp and G is the gain of first stage.							
For simplicity following stages are ignored.							
Input losses (roofing filter)			3	dB	NF of first stage is 3dB		
Noise figure of first RF amplifier			1.8	dB	F = antilog (1.8/10) = 1.514		
Gain of first RF Amp			20	dB	G = antilog(20 / 10) = 100		
Noise figure of mixer			5	dB	F = antilog (5/10) = 3.162		
NF = 3 + 10log(1.514 + (3.163 – 1 / 100)) = 4.89 dB							
Overall noise figure			**4.86**	**dB**			
Based on ktB ie -174dBm/Hz							
Deviation		+/-	2000	Hz			
Mode Freq			2000	Hz			
Max carrier error			5000	Hz			
Noise bandwidth			13000	Hz	**41.2**	**dB**	
Noise figure			**4.89**	**dB**			
S/N ratio required			**10**	**dB**			
Input sensitivity =		**174 - 41.2 - 4.86 - 10 = -117.9dBm**					

Table 4 Transponder Receiver Sensitivity

If the node transmitter power is 20dbm EIRP (100mW) and assuming 0db antenna gain at the meter.

Total link budget = 20 + 117.9 = **137.9db.**

The calculated path loss is 112.8dB so the margin is **25.1dB** for the "interrogate" path to the electricity meters.

184 MHz DFSK "Response" Receiver Sensitivity (mounted in the Node)							
Noise power = kTB = -174dBm / Hz							
NF= NF1 + (NF2 -1)/ G							
Where NF is overall noise figure, NF2 is noise figure of the first RF amp and G is the gain of first stage.							
For simplicity following stages are ignored.							
Input losses (roofing filter)			1.5	dB	NF of first stage is 1.5dB		
Noise figure of first RF amplifier			1	dB	F = antilog (1/10) = 1.26		
Gain of first RF Amp			20	dB	G = antilog(20 / 10) = 100		
Noise figure of mixer			5	dB	F = antilog (5/10) = 3.162		
NF = 1.5 + 10log(1.26 + (3.163 -1 / 100)) = 2.61 dB							
Overall noise figure			**2.58**	**dB**			
Based on ktB ie -174dBm/Hz							
Deviation		+/-	25000	Hz			
Mode Freq			5000	Hz			
Noise bandwidth			180000	Hz	**52.55**	**dB**	
Noise figure			**2.58**	**dB**			
S/N ratio required			**14.5**	**dB**			
Input sensitivity =		**174 - 52.55 - 2.58 - 14.5 = -104.4dBm**					

Table 5 Node Receiver Sensitivity

If the meter transmitter power is 20dbm EIRP (100mW) and assuming 0dB antenna gain at the node.

Total link budget = 20 + 104.4 = 124.4dB.

The calculated path loss is 112.8dB so the margin is **11.6dB** for the "response" path from the meters.

The above calculations show that the using the 'flat earth propagation model' there will be adequate margin in the link budget to allow for good communications between the meter and Yorkshire Electricity Group PLC Node. Note that while the link is not balanced which would be the ideal conditions there is no reason to modify the system to bring it into balance.

5.9 Preliminary Feasibility Trial

A preliminary trial was conducted to establish if the path loss of 112.8dB for 750 metres calculated above was reasonable.

The trial consisted of placing a 100mW CW transmitter at a position in a typical location at the Yorkshire Electricity Group PLC site at Lindley north east of Huddersfield and moving a receiver around to establish received signal strengths.

The transmitter was constructed using a simple overtone crystal oscillator running at 61.333MHz which was then multiplied by 3 and filtered using a 3 chamber helical filter. The resulting signal was amplified and the output of 184MHz at +22dBm was fed via a length of RG174 (2db insertion loss) to a commercial end fed monopole antenna mounted on top of a 3 metre wooden pole. The 3dB gain of the antenna was compensated for with a 3dB coaxial attenuator mounted at the base of the antenna.

The mobile receiver consisted of a commercial mobile dipole antenna, similar to the one in figure 45 on page 113, mounted on a 1 metre wooden pole. This antenna had the 'ground' section of the dipole replaced with a short helical element to reduce the physical size of the antenna. This antenna fed an amplifier with noise figure of 3dB and 26dB gain (Mini-Circuits unit); the amplified received 184MHz signal was then fed into a spectrum analyser and displayed on the screen. Note the amplifier was used to minimise as much as possible the noise figure of the spectrum analyser which was in the order of 30 dB.

Reception at 750 metres using this set up was not feasible as a spectrum analyser is not optimised to receive a narrow band signal off air. To over come the 30dB noise figure of the spectrum analyser at least that much gain must be placed in front of the analyser preferably much more.

$$NF = NF1 + (NF2 - 1)/G$$

$$NF = 3 + 10\log(1000 - 1 / 398.1) = 7\text{dB}$$

Even if the front end gain is increased giving a lower noise figure the noise band width of the spectrum analyser is such that the noise floor of this measurement system is only approximately -80dBm.

A more sophisticated measurement unit could have been designed and built but at this early stage, prior to bidding for the contract, this was not economically realistic. The measurement system did show that the calculated path loss was not unreasonable at smaller ranges and that the system as described in this thesis would work. Once the contract was awarded a more sophisticated technology demonstrator was designed and this is described in the next section.

5.10 Technology trial

This was again conducted at Lindley, the goal of this trial was to demonstrate the data gathering accuracy of the proposed electricity meter plus radio set up and if possible to gather some range versus signal strength information.

The technology trial utilised the Siemens S2AS electronic single phase electricity meters and these were connected in series with the existing electricity meter which was used to collect the billing information and act as a control for this trial. Note the Siemens S2AS meter is further described in the Customer Trial implementation paragraph below.

For the Technology Trial some high cost electronic short cuts were taken. The electricity meter transponder transmitter was designed using an Analog Devices AD9831 direct digital synthesis IC which generated the GMSK signal at 10.7MHz. This was filtered in ceramic filters and up converted using a Motorola MC13143 mixer IC to 184MHz where it was again filtered and amplified ready for transmission. The receiver was a double conversion superhetrodyne design based around a Motorola MC3363DW. The transmit/receive switch was implemented with a Triquint TQ9155 IC. The antenna was a commercial (Panorama Antennas) dipole fitted outside of the transponder box, something that would not be allowed in the customer trial due to the risk of tampering. The data gathering and radio control was performed by a Microchip PIC17C43 microcontroller.

75 of these transponders were built and tested and 66 of them where eventually mounted in homes in Lindley, see table 6.

Customer Address 1	Customer Address 2	Customer Address 3	Survey Signal Strength (dBm)
15 Gatesgarth Crescent	Lindley	Huddersfield	-69.6
20 Gatesgarth Crescent	Lindley	Huddersfield	-70.3
80 Chiltern Ave	Lindley	Huddersfield	-70.0
76 Chiltern Ave	Lindley	Huddersfield	-70.0
70 Chiltern Ave	Lindley	Huddersfield	-69.7
64 Chiltern Ave	Lindley	Huddersfield	-69.5
22 Mendip Ave	Lindley	Huddersfield	-67.1
16 Mendip Ave	Lindley	Huddersfield	-68.5
44 Brecon Ave	Lindley	Huddersfield	-70.2
26 Brecon Ave	Lindley	Huddersfield	-69.1
56 Low Hills Lane	Lindley	Huddersfield	-69.4
50 Low Hills Lane	Lindley	Huddersfield	-69.6
46 Low Hills lane	Lindley	Huddersfield	-69.3
44 Low Hills lane	Lindley	Huddersfield	-69.2
62 Crossland Road	Lindley	Huddersfield	-69.8
56 Crossland Road	Lindley	Huddersfield	-70.0
52 Crossland Road	Lindley	Huddersfield	-70.6
48 Crossland Road	Lindley	Huddersfield	-70.2
10 Sandmoor Drive	Lindley	Huddersfield	-68.7
12 Sandmoor Drive	Lindley	Huddersfield	-68.7
16 Sandmoor Drive	Lindley	Huddersfield	-68.7
7 Sandmoor Drive	Lindley	Huddersfield	-69.6
81 Kirkwood Drive	Lindley	Huddersfield	-69.5
34 Temple Street	Lindley	Huddersfield	-68.3
27 Brian Street	Lindley	Huddersfield	-69.3
35 Brian Street	Lindley	Huddersfield	-67.1
47 Brian Street	Lindley	Huddersfield	-69.1
65 Thomas Street	Lindley	Huddersfield	-65.2
73 Thomas Street	Lindley	Huddersfield	-65.6
5 Adam Court	Lindley	Huddersfield	-68.9
1 Adam Court	Lindley	Huddersfield	-69.5
43 Thorncliffe Street	Lindley	Huddersfield	-69.6
45 Thorncliffe Street	Lindley	Huddersfield	-69.1
49 Thorncliffe Street	Lindley	Huddersfield	-69.8
7 Dearne Fold	Lindley	Huddersfield	-67.1
20 Dearne Fold	Lindley	Huddersfield	-69.8
4 Ryecroft Drive	Lindley	Huddersfield	-69.1
7 Rycroft Drive	Lindley	Huddersfield	-69.1
8 Cowrakes Rd	Lindley	Huddersfield	-69.8
3 Fern Lea Flats	Lindley	Huddersfield	-69.4
4 Fern Lea Flats	Lindley	Huddersfield	-69.1
9 Fern Lea Flats	Lindley	Huddersfield	-68.5
14 Fern Lea Flats	Lindley	Huddersfield	-70.2
22 Fern Lea Flats	Lindley	Huddersfield	-70.4
35 Birchencliffe Hill road	Lindley	Huddersfield	-70.4
3 Zion Close	Lindley	Huddersfield	-68.9
7 Zion Close	Lindley	Huddersfield	-68.7

13 Zion Close	Lindley	Huddersfield	-70.2
17 Zion Close	Lindley	Huddersfield	-69.1
66 Lidgett Street	Lindley	Huddersfield	-69.0
64 Lidgett Street	Lindley	Huddersfield	-70.0
62 Lidgett Street	Lindley	Huddersfield	-69.3
54 Lidgett Street	Lindley	Huddersfield	-70.4
33 Holybank Road	Lindley	Huddersfield	-70.6
37 Hollybank Road	Lindley	Huddersfield	-69.5
41 Hollybank Road	Lindley	Huddersfield	-69.8
23 Briarlyn Road	Lindley	Huddersfield	-69.6
33 Briarlyn Road	Lindley	Huddersfield	-69.1
35 Briarlyn Road	Lindley	Huddersfield	-69.9
43 Briarlyn Road	Lindley	Huddersfield	-69.8
67 Briarlyn Avenue	Lindley	Huddersfield	-67.3
126 Briarlyn Road	Lindley	Huddersfield	-68.9
118 Briarlyn Road	Lindley	Huddersfield	-69.4
114 Briarlyn Road	Lindley	Huddersfield	-69.6
108 Briarlyn Road	Lindley	Huddersfield	-69.8
106 Briarlyn Road	Lindley	Huddersfield	-68.9
Max survey signal= 65.2dBm	Min = -70.6dBm		

Table 6 TTS transponders in Lindley

The data concentrator was designed using a simple Digital Frequency Shift Keying (DFSK) transmitter design to wake up the transponders based around the 100mW CW crystal transmitter used before but with the crystal pulled by a varacter diode controlled by the a data stream, in this case the wake up signal. This was generated in a PC as part of the DATA Concentrator / billing system simulation. The transmit/receive antenna was an end fed monopole mounted on a mast some 3 metres above the ground. The node receiver consisted of an LNA amplifier feeding a down converter driven by crystal oscillator which then fed a fast Analogue to Digital converter and into a Digital Signal Processor which performed the GMSK demodulation, clock recovery and serial to parallel conversion prior to outputting the data to the Data Concentrator emulation running on the PC.

The technology trail was limited in time and very little useful data was gathered, however it did show that all the electricity meter transponders could be read after the transponders were positioned such that the path loss was not excessive. The excessive path loss was likely caused by shadowing or some other mechanism as described in chapter 4.

5.11 Customer Trial at Goole

5.11.1 Implementation

The AMR system employs a cellular radio architecture, working in the 184MHz frequency band, which is dedicated exclusively to utility meter reading in the UK, to provide a local area network (LAN) to collect data from domestic (Siemens S2AS-100) and industrial (PRI CALMU) electricity meters. Each electricity meter is fitted with a Radio Transponder which transmits consumption data to a data concentrator or Node. The collection of data is implemented on a scheduled basis, although there is also provision for real time interrogations of individual meters if for instance the customer has decided to move house and requires an instant bill.

The Siemens S2AS-100 electronic electricity meters, as shown in figure 43, were chosen for this trail as they provide an EN 61107 optical interface to the internal registers of the electricity meter that contain the consumption readings. Additionally there was an existing moulded enclosure that fitted over the Siemens S2AS-100 meter. This enclosure allows access to mains power and provides space to mount the 184MHz transponder and associated circuitry. This enclosure was originally designed for use as a pre-paid meter and coin receptacle. Note that all parts of the transponder including the antenna had to be fitted inside the enclosure and had to meet all CE safety standards.

Figure 43 Siemens S2AS – 100 single Phase Electricity Meter

The Siemens S2AS-100 electricity meters were fitted at the 2500 customer sites who were participating in the trial and initial meter readings taken. Some of the meters were installed in a meter cabinet on an external wall while the majority of the meter mounting points where at the house access point (HAP) usually internally by the front door or under the stairs. Those meters that were on an external wall might be on a wall facing the node or at the back of the house or often on a side wall in an alley way between houses.

Some light industrial sites were fitted with PRI Calmu 3-phase electricity meters, as seen in figure 44, also having an EN 61107 optical interface giving access to their internal registers.

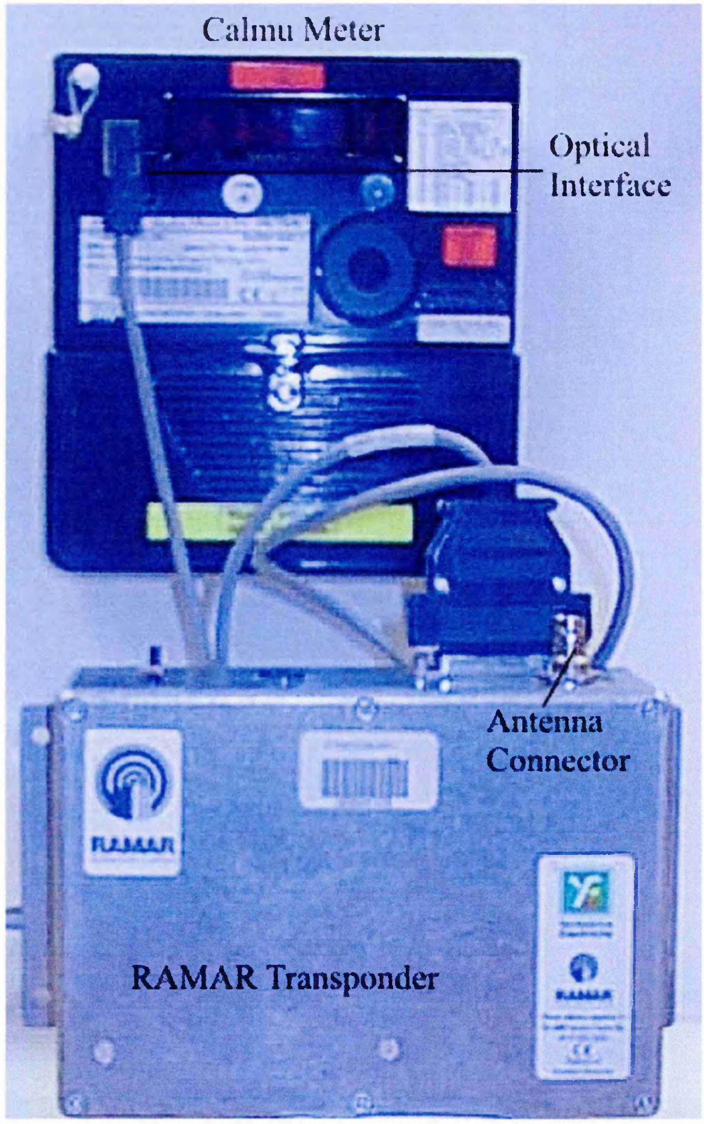


Figure 44 Calmu multi-phase electricity meter and Yorkshire Electricity Group PLC Transponder

These sites required a different more robust communications device and were fitted with a Yorkshire Electricity Group PLC transponder mounted in a die cast metal box. This transponder had different firmware to allow for access to the registers in the Calmu meter. While the electronic circuits of the transponder were the same as those used on the Siemens S2AS-100 domestic electricity meter the die cast box gave better screening and made the setup more rugged. The power supply was in this case by an external OEM plug top power supply and an external 184MHz dipole antenna was used as shown in figure 45. Several of these commercial sites such as Hotels and office buildings had the Calmu 3-phase electricity meter located in the basement. These sites required careful choice of antenna position to allow for a good communications channel and we adopted the routine of placing a 6dB attenuator pad in the antenna lead when installing the antenna and logging the meter transponder with the relevant Node. In this way during normal operation with the attenuator removed there would be an additional 6dB of signal strength in both directions providing an increased reliability in communications.

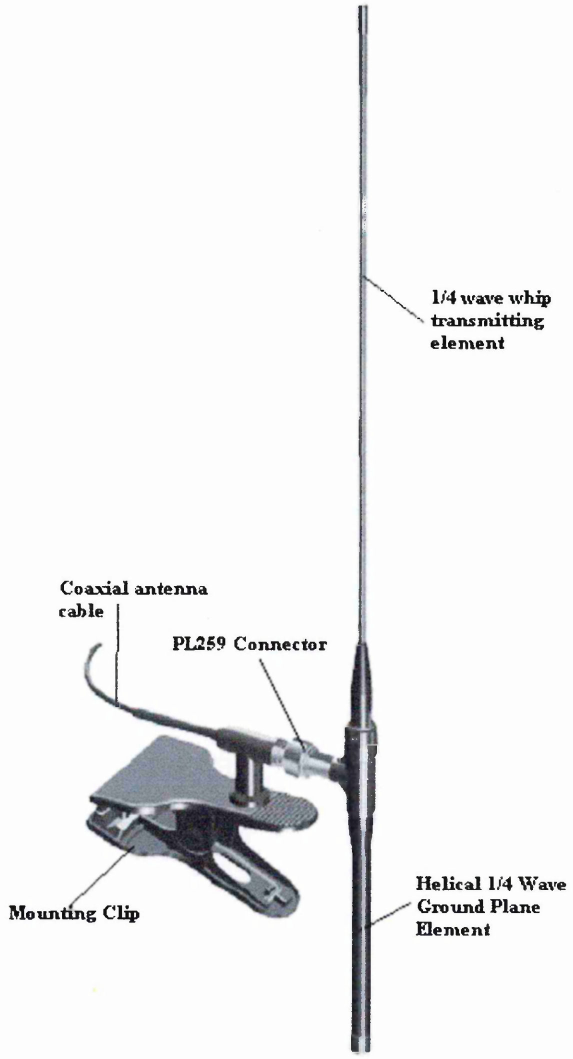


Figure 45 Panorama Antennas 184 MHz Dipole

Other arrangements for collecting data from CALMU meters which are not equipped for AMR functionality require a land line per Utility meter or the use of an alternate communications channel such as a commercial radio link (Pacnet at 173.25 MHz) or leased telephone line with auto-dialler so the use of a dedicated AMR system illustrates the opportunity for reducing operational costs which is another important potential benefit of implementing AMR. The case is further supported by reduced reliance on manual reads, and the elimination of return visits to 'difficult to read' premises.

5.11.2 Yorkshire Electricity Group PLC transponder

The Yorkshire Electricity Group PLC transponder was designed to fit onto the Siemens S2AS electricity meter to gather meter readings every 30 minutes. The Transponder consists of 3 PCBs, the power supply and optical interface to the Siemens electricity meter PCB, the RF PCB and the Antenna PCB. The antenna for the customer trial was required to be non visible and that meant installing it inside the plastic case of the transponder. The problem was that the wavelength at 184MHz was 1.63metres thus a dipole would be approximately 800 mm long. An antenna was designed to be etched on a PCB thus being cheap to produce but would be as good as the dipole used during the Technology Trial. In fact as shown it the polar diagram, as shown in figure 46, the PCB antenna while a little lower in gain the polar diagram is much more consistent in gain with no reduction in any direction. This means the installation of the transponder should be easier and more predictable.

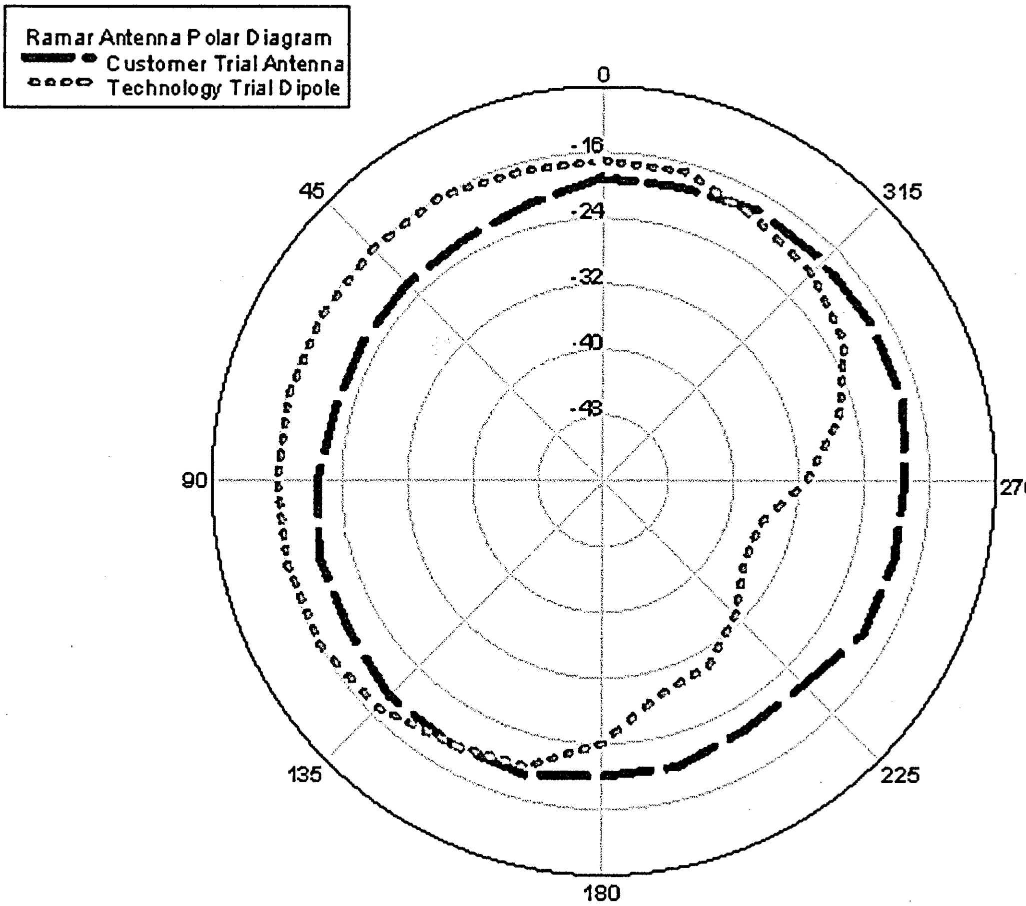


Figure 46 Polar Diagrams of Dipole versus internal antenna

The transponder fits fully over the Siemens S2AS electricity meter and can be securely fastened to the Electricity meter to reduce or eliminate tampering as shown in figure 47. There is a cut out in the Transponder so that the Siemens S2AS electricity meter's LCD screen can still be seen. Within the transponder as shown in figure 48 the power supply board picks up 240 volts AC from the S2AS electricity meter and converts it to the required low voltage DC. Also on the power supply board a PIC 12C56 processor controls the EN 61107 optical interface to the internal registers of the electricity meter and passes the data to the main processor on the RF PCB.

The radio PCB has a 184MHz transmitter and receiver on it. The main processing power is supplied by a PIC17C44 microprocessor with 16kbytes of internal program memory, 454 bytes of ram. There is a further 1 k byte of EEPROM organised as 128 by 8 bytes addressed via the I^2C bus. This EEPROM is used to store the soft ID as well as up to 2 ½ days of half hourly meter records. That is addition to the 7 days worth of readings that may be stored in the Siemens S2AS electricity meters.

The receiver was a double conversion superhetrodyne design based around a Motorola MC3363DW. The transmit/receive switch was implemented with using 2 pin diode switches controlled by the PIC17C44 processor. The transmitter was again a GMSK design but this time it was implemented using op amps and discrete transistors driven by the PIC17C44.

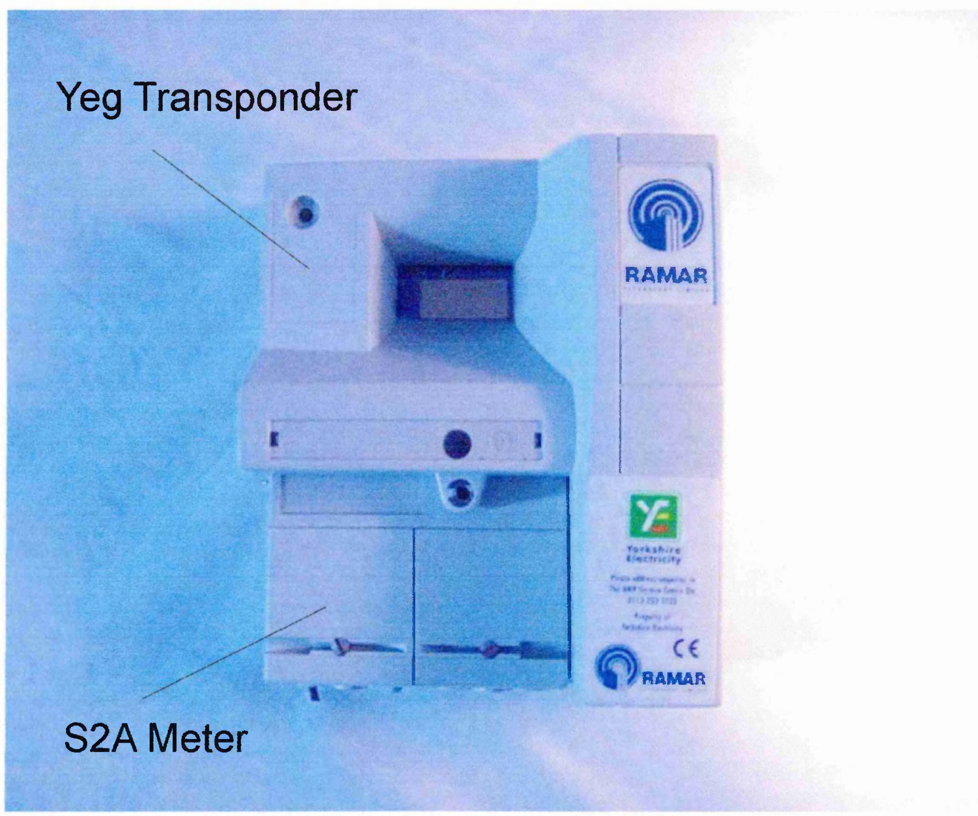


Figure 47 Yorkshire Electricity Group PLC Transponder mounted on Siemens S2AS Electricity Meter

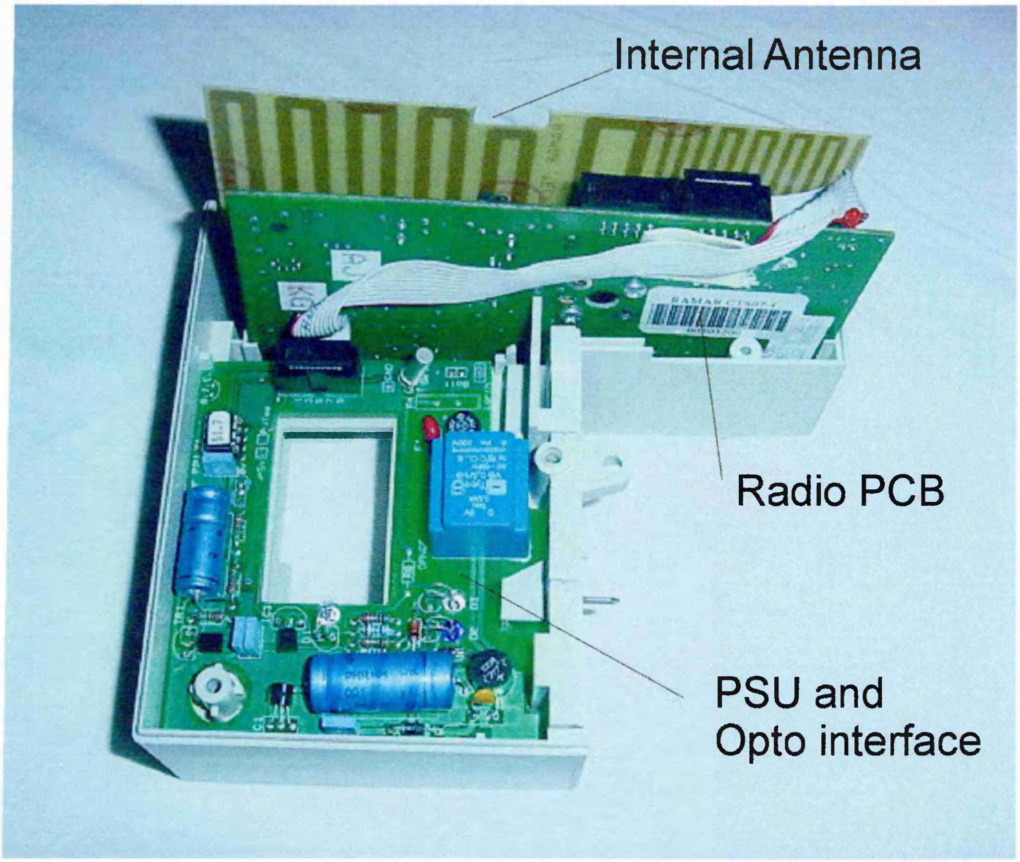


Figure 48 Internal Components of Yorkshire Electricity Group PLC Transponder

The PCBs where manufactured at ACW ltd in Wales and are laid out for inspection in figure 49.

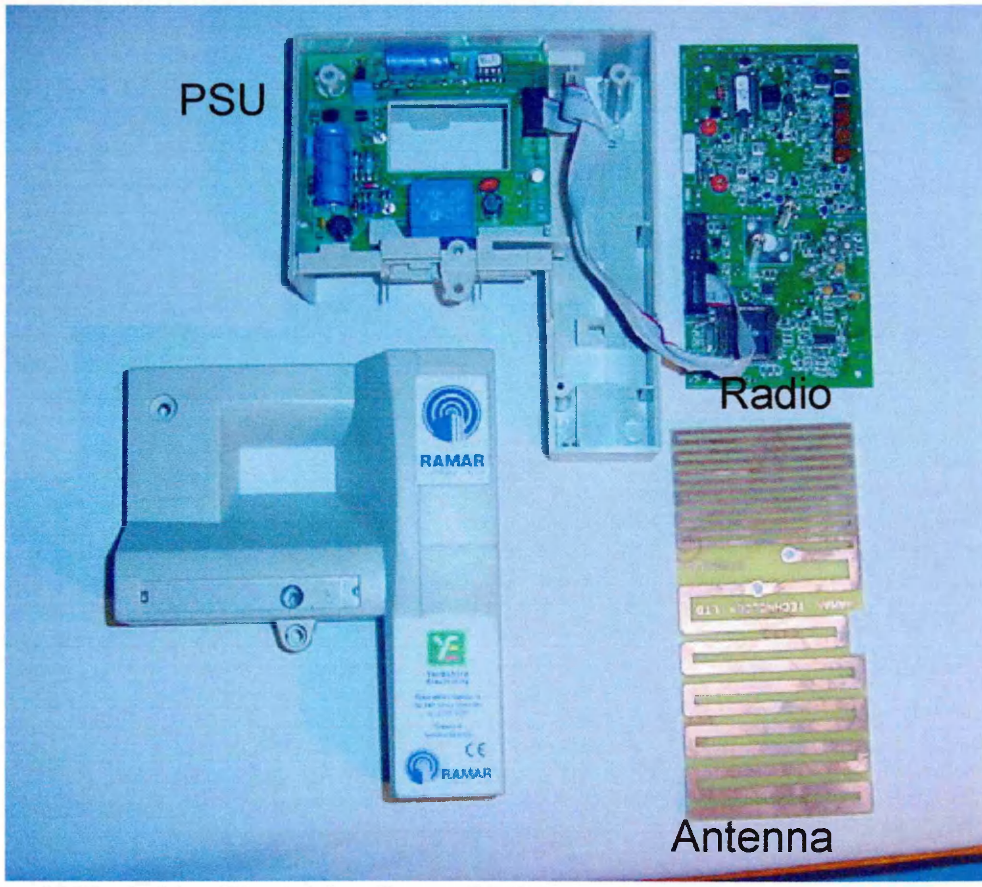


Figure 49 Yorkshire Electricity Group PLC Transponder internal components laid out for inspection

5.11.3 Data Concentrator or Node

Each Yorkshire Electricity Group PLC Node acted as a data concentrator for its cell, the Node interfaced with a third party Wide Area Network (WAN) to transfer the collected data to a central server at an AMR station, in this case Yorkshire Electricity Group PLC headquarters in Leeds. The British Telecom PSTN services were chosen as the 'wide area network' for the purposes of the Yorkshire Electricity Group PLC trials and landlines were run to those Utility sub station and other node sites that did not have them already fitted. The Node also provided timing information to the electricity meter transponders and controlled any retransmissions caused by corrupted data during reception from any transponder. Additionally the Node would contact the main server in the event of a power outage or other unexpected event such as tampering.

Each Node in the trial could support 512 electricity meters but future solutions would not be constrained to this number and each Node required a single British Telecom land line for connection back to the central server. The scheduled connection to the server was chosen by the server and was usually late at night during quiet periods on all networks; each Node would be contacted in turn.

The Yorkshire Electricity Group PLC Node as shown in block diagram form in figure 50 consisted of 4 main units fitted into a lockable wall mounting metal case as shown in figure 51 and figure 52; there were 4 external connections and these were a BT line, Mains input at 240v AC and two antenna connections to external antennas. The external antennas could be of omni directional type for all round coverage or a directional antenna depending on the geography of the cell that the Yorkshire Electricity Group PLC Node is servicing. Note that the directional antenna will give increased gain and possible reduction in noise but with reduced cell coverage. The provision of two antennas was to add some spatial diversity. Spatial diversity can minimise the chances that any meter transponder would be in a radio null and thus would have poor communications performance.

The 4 main units of the Yorkshire Electricity Group PLC Node include the 184MHz DFSK transmitter and MSK radio receiver unit with performance listed in Appendix 3, Data recovery unit, PC type Processor unit, and power supply unit with battery backup. The transmitter in the Yorkshire Electricity Group PLC Node transmitted a Manchester encoded DFSK wakeup signal to all of the transponders who respond in their allocated time slots with the meter reading and their soft ID. Note that the Yorkshire Electricity Group PLC Node monitored the communications channel and would only transmit a transponder wake-up message if the communications channel was clear. The output from the Yorkshire Electricity Group PLC Node receiver was a stream of transponder responses at slightly different centre frequencies, clock rates, and amplitudes and this data stream was converted to digital in the A to D converter and passed through a data/clock recovery circuit which extracted the data clock and then squared up and retimed the data.

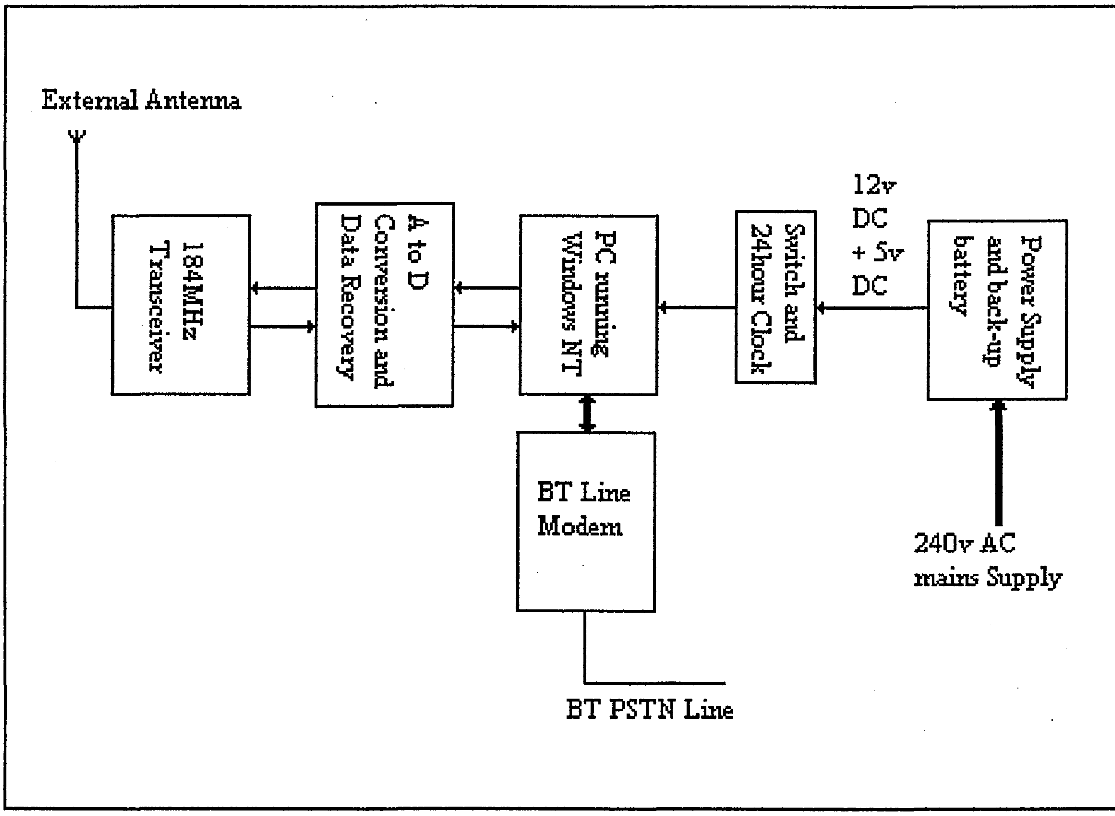


Figure 50 Yorkshire Electricity Group PLC Node or Data Concentrator Block Diagram

The data was then processed by the PC so that each Transponder soft ID could be extracted and the associated meter reading stored against that transponder. This would only happen if the CRC and other error checks had passed and the transponder soft ID was recognised by the Node.

Also in the Node was a power supply unit that conditioned the mains input power and converted it for use by the rest of the Node circuits. This power supply was fitted with back up batteries in case of power failure during the trial. The batteries were of sufficient capacity to allow full system operation for 60 minutes and data retention for a further 24 hours. In the event of a power failure the Node would automatically send a message to the Billing computer at the Yorkshire Electricity Group PLC main office.

A timed switch was later fitted between the power supply and the PC to perform a hard reset every 24 hours during the early hours of the morning as a serious software bug was found in the Windows NT operating system when operating with the real time extensions. As this software bug was part of the operating system and could not be compensated for in the system software a hardware solution was applied.

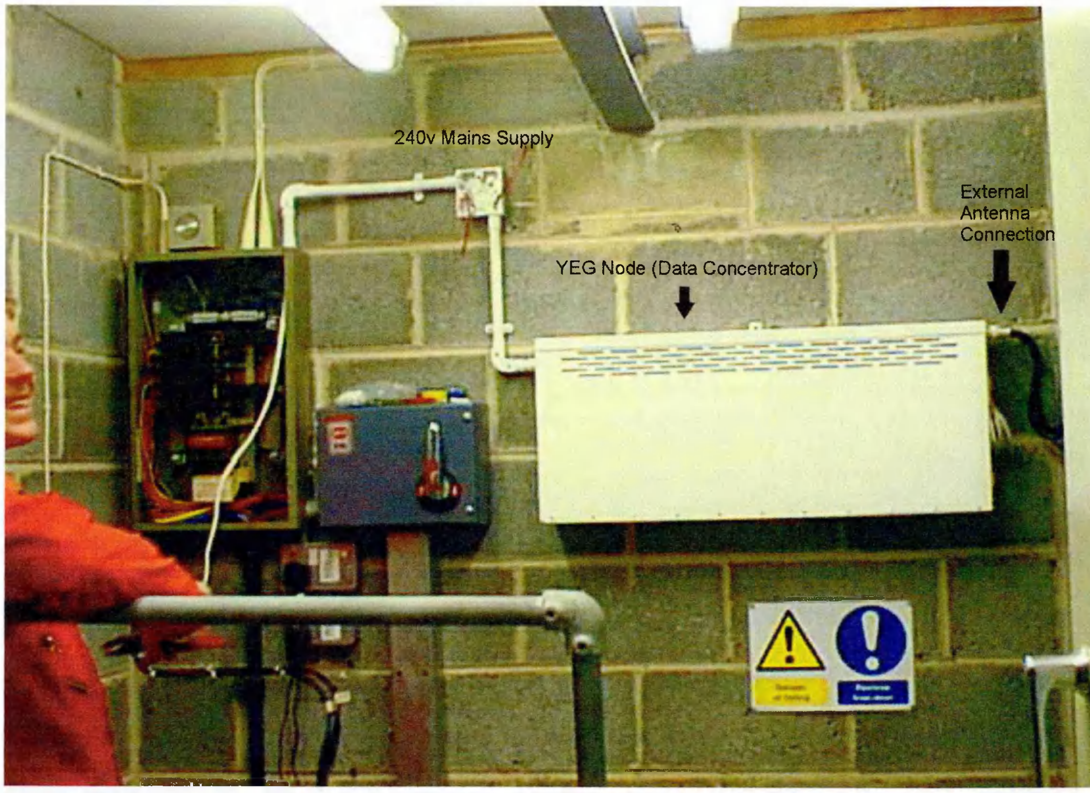


Figure 51 Yorkshire Electricity Group PLC Node mounted in electricity Sub-Station


Figure 52 Fully installed Yorkshire Electricity Group PLC Node showing twin antenna connections

The AMR Nodes interfaced with the Yorkshire Electricity Group PLC internal computer network with appropriate firewall protection. This enabled AMR data to be made available to other business systems such as billing and system monitoring. The availability of half hourly data enables more accurate forecasting of future supply requirements than has previously been possible. This offers the potential for significant savings when dealing in the Electricity Trading Pool.

The system also offers a number of other 'added value' services. This includes the generation of exception reports for meter tampering, reverse flow and power outages. These are transmitted to the Node which passes an event log of these incidents as part of its scheduled download to the AMR station. Power outages which persist for a 2 minute period generate a 'real time alarm sense'. This is transmitted to the Node which passes it to the AMR station immediately. An interface to existing system performance applications enables this outage data to be used in identifying the source of a problem and speeding up remedial action, hence improving the level of service to the customer.

5.11.4 Actual CTS Trial

Seven Nodes were manufactured in house at RAMAR Ltd and six were installed at the following locations in Goole, Yorkshire. The last unit was kept at RAMAR Ltd as a spare.

1 Pasture Road School
2 Prospect House Day Care Centre as shown in figure 53
3 Park side School
4 Woodlands Road Public House as shown in figure 54 and figure 55
5 Kingsway School
6 Queensway Electricity Sub station as shown in figure 56 and figure 57

Note that the Parkside School node did not have many transponders installed.

Figure 53 Prospect House Day care centre with Dual Yagi antennas

Figure 54 Woodlands Public House Node

Figure 55 Woodlands Public House Node showing twin Yagi antennas

Figure 56 Queensway Electricity Sub Station

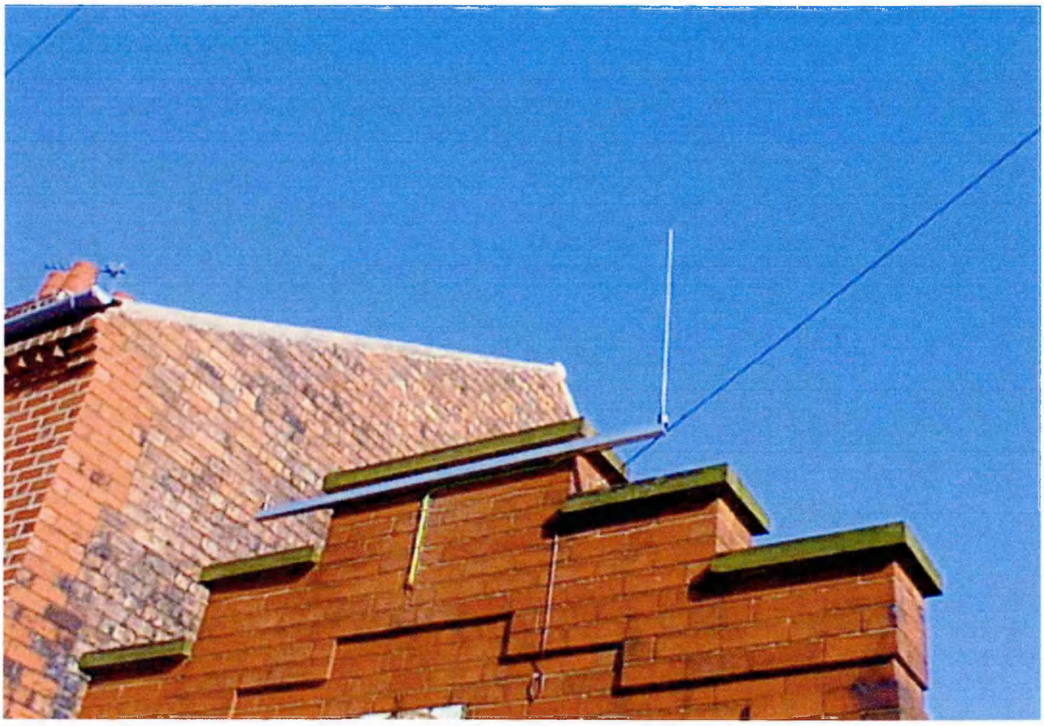


Figure 57 Queensway Electricity Sub Station showing single omni antenna

The electricity meter transponders where installed in 2000 premises in various areas of Goole and as each one was installed it was logged onto to the Node that had received the transponders signal and had the strongest signal strength, the transponder was then issued with a soft ID and a timeslot by the Node. The signal strength was measure by utilising a Signal Strength Indicator (SSI) output of the IF amplifier in the Yorkshire Electricity Group PLC Node receiver from the response sent by the transponder. This installation process was necessary so that each transponder installation could be allocated a timeslot to respond to its own Node and so that the transponder would recognise only its own node wake-up message. The installation sequence was automatic once it had been triggered by placing a strong magnet near a reed switch mounted inside the transponder. Note that once the transponder had been successfully logged onto a node it would require a full firmware reload before the installation process could be triggered again.

During the Technology Trial it was found that several installation attempts were required to find the optimum 'radio' site for each S2AS electricity meter so that its associated transponder was not in a radio signal null. Thus special battery powered transponders with a serial number of zero and push button installation trigger in place of the magnet / reed switch were manufactured. These would trigger the timeslot installation process and light an LED when successful but not actually log onto a specific node. In this way the installation technicians could make repeated trials with the same transponder prior to mounting the S2AS electricity meter and radio transponder. The installers became most proficient at this task.

The electricity meter and transponder location where then married up to the Soft ID for that transponder using a data base generated in Psion hand held computers during the installation process. The installation technicians would log the time and location of the meter and transponder as well as scanning the serial number bar codes for both the meter and transponder. Once the address was known a post code could be assigned to each electricity meter. Given the post code and house number a computer program was used to generate longitude and latitude for that transponder. Using the longitude and latitude of both the transponder and the node the range could be calculated. An extract of the post code data base is shown in table 7.

Soft ID	Name and Address	Post Code
00002059	MR M & MRS K XXXXXX67 MARSHFIELD RD	DN14 5JQ
0000205A	MR R XXXXXX60 MARSHFIELD RD	DN14 5JG
0000205B	MS B B XXXXXX32 MARSHFIELD RD	DN14 5JQ
0000205D	MR AXXXXXXXX50 MARSHFIELD RD	DN14 5JG
0000205E	MRS P D XXXXX70 MARSHFIELD RD	DN14 5JG
0000205F	MISS G XXXXX48 MARSHFIELD RD	DN14 5JG
00002061	MR R & MRS P XXXXX12 BROADWAY	DN14 5HR
00002062	MR & MRS P R XXXXXX28 BROADWAY	DN14 5HR
00002063	MR T XXXXXXXXXXXX18 BROADWAY	DN14 5HR
00002064	MR J A XXXXX6 MARSHFIELD AVE	DN14 5JH

Table 7 Extract of POST CODE DATABASE

The data was held in the internal registers of each transponder until the respective nodes issued a wake up signal to their transponders. This was on a half hourly schedule day and night and each node listened to the channel prior to transmitting its wakeup signal. The nodes were given schedule times and their internal clocks updated each time they logged onto the main server at the utility head quarters at the White House in Leeds. The downloading of data from the Nodes took place once per day in the middle of the night and was made by leased telephone line and 56k telephone modem.

Once the data was received by the main server it was processed and stored ready for access by the processes requiring the data such as billing and consumption prediction. This data contained the following fields:- address including soft ID, house number and road, meter details including meter serial number, which utility owned meter, for future use, meter type including meter code and meter mount description, a special Power Alarm Field including node ID and alarm time stamp, a range field associated with each soft ID and a reading field including reading time stamp, actual meter reading and signal strength. Note that some readings were appended by the Node during the data gathering process such as signal strength and some added at the main server data base such as meter type and range information.

The data base was interrogated to produce data required for investigating the propagation characteristics as detailed in Chapter 6. An example of the queries used and the output from one of those queries is shown in figure 58 and figure 59.

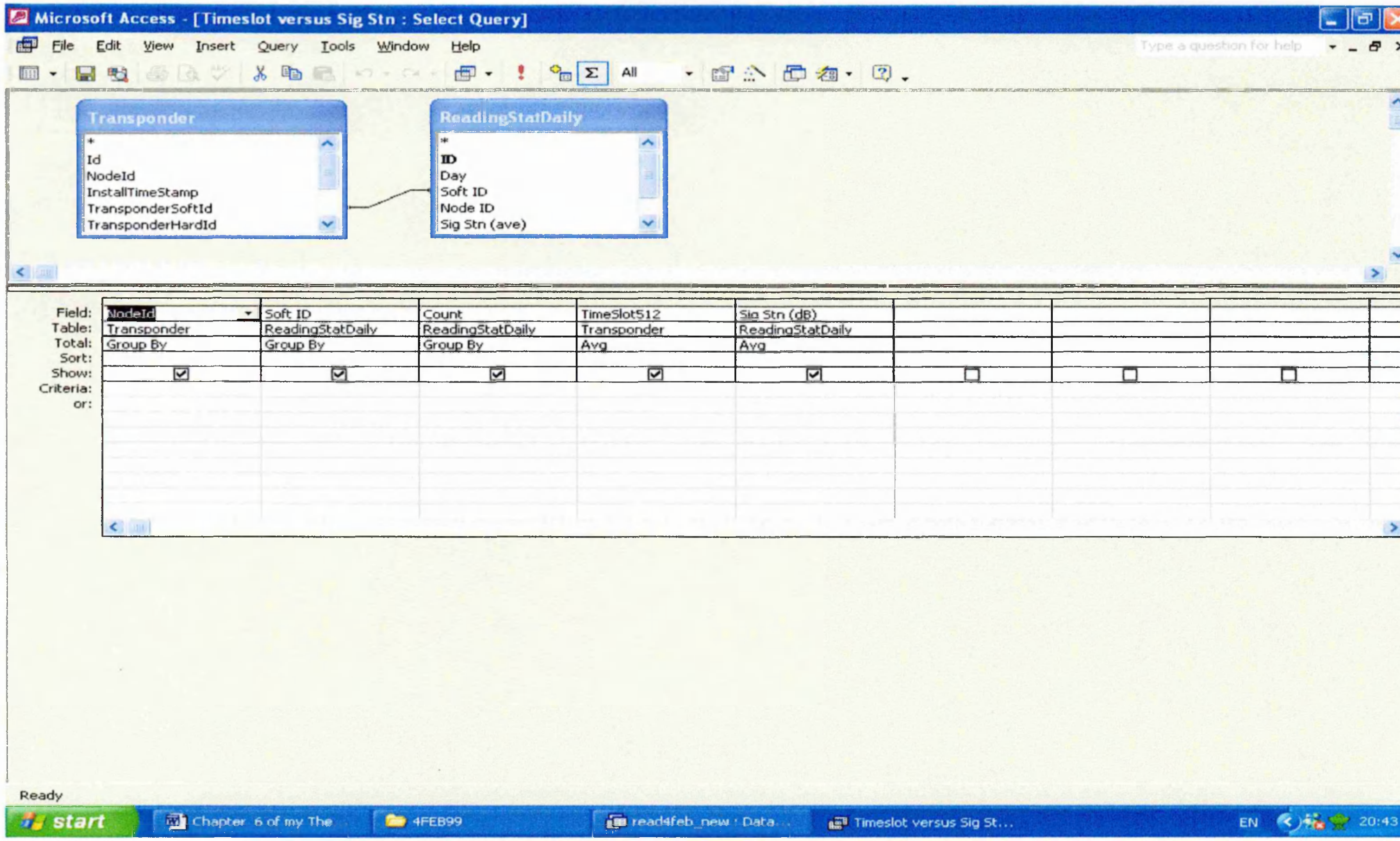
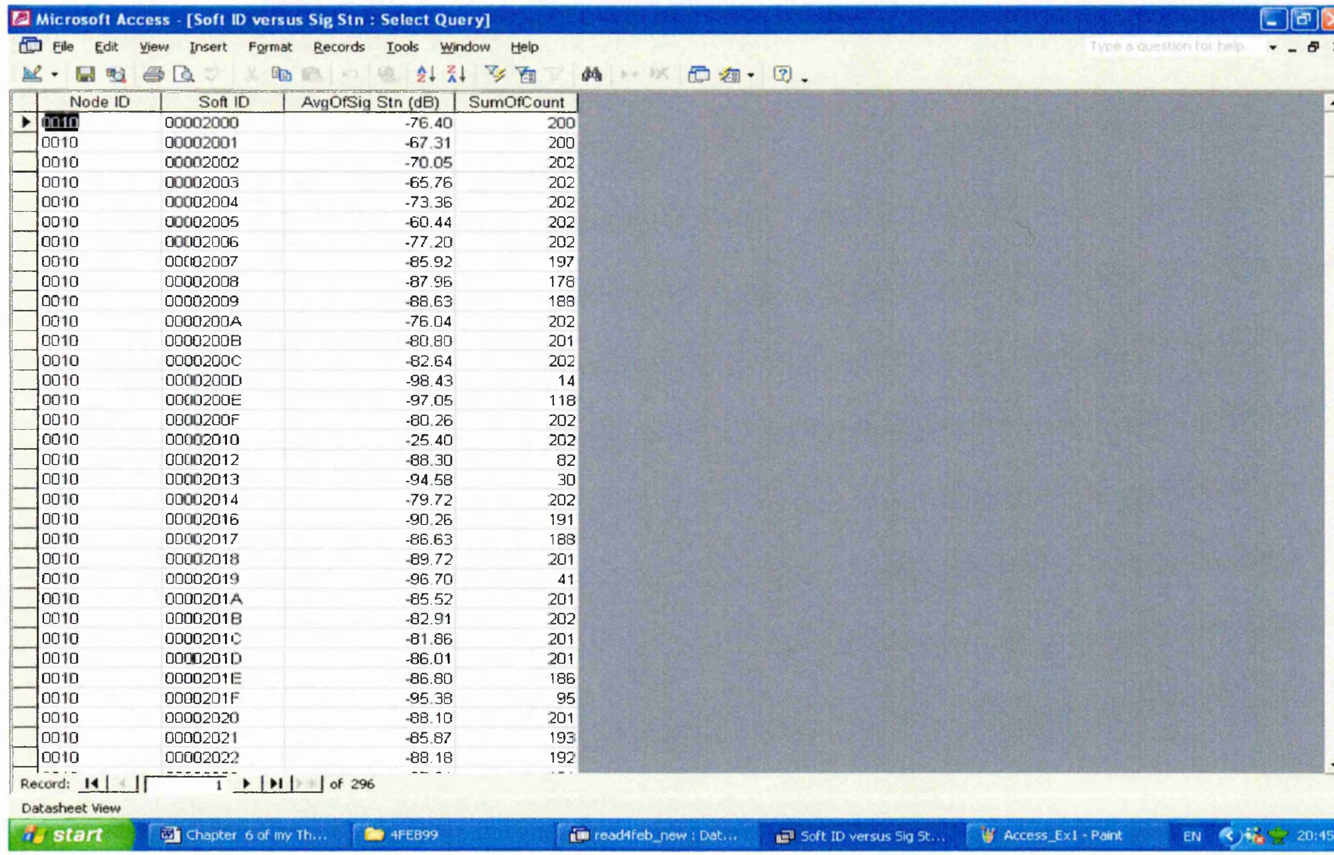


Figure 58 an example of an access query



Node ID	Soft ID	AvgOfSig Stn (dB)	SumOfCount
0010	00002000	-76.40	200
0010	00002001	-67.31	200
0010	00002002	-70.05	202
0010	00002003	-65.76	202
0010	00002004	-73.36	202
0010	00002005	-60.44	202
0010	00002006	-77.20	202
0010	00002007	-85.92	197
0010	00002008	-87.96	178
0010	00002009	-88.63	188
0010	0000200A	-76.04	202
0010	0000200B	-80.80	201
0010	0000200C	-82.64	202
0010	0000200D	-98.43	14
0010	0000200E	-97.05	118
0010	0000200F	-80.26	202
0010	00002010	-25.40	202
0010	00002012	-88.30	82
0010	00002013	-94.58	30
0010	00002014	-79.72	202
0010	00002016	-90.26	191
0010	00002017	-86.63	188
0010	00002018	-89.72	201
0010	00002019	-96.70	41
0010	0000201A	-85.52	201
0010	0000201B	-82.91	202
0010	0000201C	-81.86	201
0010	0000201D	-86.01	201
0010	0000201E	-86.80	186
0010	0000201F	-95.38	95
0010	00002020	-88.10	201
0010	00002021	-85.87	193
0010	00002022	-88.18	192

Figure 59 An example of the results of an access query

5.12 Summary

Chapter 5 has described both the Nimbus power line carrier trials carried out in conjunction with Symbol Seeker and the radio link trials of an automated meter reading system carried out in conjunction with Ramar Technology. Chapter 6 will analyse the results of the trial most especially the CTS trial at Goole in West Yorkshire and present the findings.

Chapter 6 Results Analysis

Introduction

Chapter 5 has described the trials undertaken for this thesis and presented the results. Chapter 6 will analyse the results especially for the Customer trial at Goole in Yorkshire and make some comparisons of the two Last Kilometre solutions and then make some suggestions for future work.

6.1 Analysis of the Nimbus Power Line Carrier Alarm System

The initial trial at the Open University site was inconclusive as confusion over phase identification and a faulty power line modem led to the Nimbus system only working over short ranges. Valuable lessons were learnt such as using the early nimbus mark 1 system as a phase identifier and to check all equipment prior and during the trials. The Nimbus did operate in the presence of noise albeit with some loss of signal confidence at the Plug-In which highlighted a software bug. The second set of trials at the Kepier site was more encouraging with hardly any attenuation experienced over a realistic distance. This was without noise or loads applied to the distribution system that will reduce the range of the Nimbus system but some of that will be overcome by the adoption of a Forward Error Correction strategy.

6.2 Statistical Analysis of the Customer Trial Data

An analysis of the two sets of data from the CTS trial in Goole was conducted. This was to ensure that any conclusions drawn were valid. The two sets of data, separated by several weeks, provided a reasonable sample for comparison and analysis.

Some concern was generated when the number of daily responses (count) from each transponder for the first set of data was plotted against time slot, as shown in figure 60.

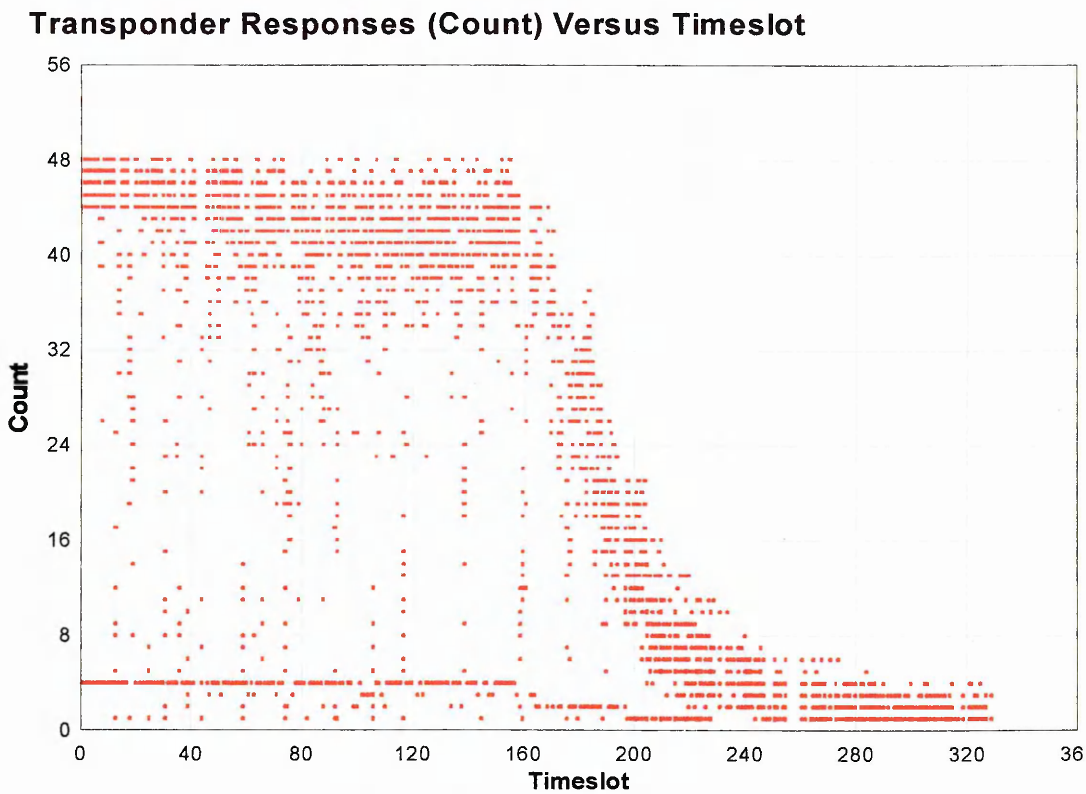


Figure 60 Plot of Transponder Responses versus Time Slot

Figure 60 shows the number of times each transponder, of all of those transponders installed on the Queensway node, responded in one day during the 9-day period. There are two main points of interest, the steep and dramatic fall-off in responses when the timeslot is above 160, and the line of responses centred on the count of 4.

Further investigation shows that the fall off happens to the 'count' or number of responses for all transponders that respond in timeslots above 150, for all nodes, on all days. To investigate this effect, RAMAR Technology conducted trials at Goole using a mobile node and some software developed in house; the phenomenon was not reproduced. The fall off has been attributed to the limitations in the real time extensions to Windows NT operating system used in the node

No other node replicates the line of responses at the count of 4 on one day but similar small numbers of count are found on other days and other nodes. These correspond to days when that particular node had crashed which were again attributed to problems with the software and operating system. A 'fix' was installed in each node that cut the power to the PC for a short period each night thus forcing a hard restart for the PC. No further effects were seen.

The distributions of the transponder responses for timeslots above 100 and below 100 were plotted. The data (timeslot <100) from the Queensway node for 1st trial is plotted in figure 61. Figure 62 shows the transponder responses from the Queensway node for timeslots above 100. Comparing the two plots, the distributions are similar. This was also the case for all other nodes. The distributions in figure 61 and figure 62 also show that there is no sharp cut off at low signal strengths. This indicates that the limit on sensitivity is due to the ambient noise floor and interference rather than some mechanism within the software.

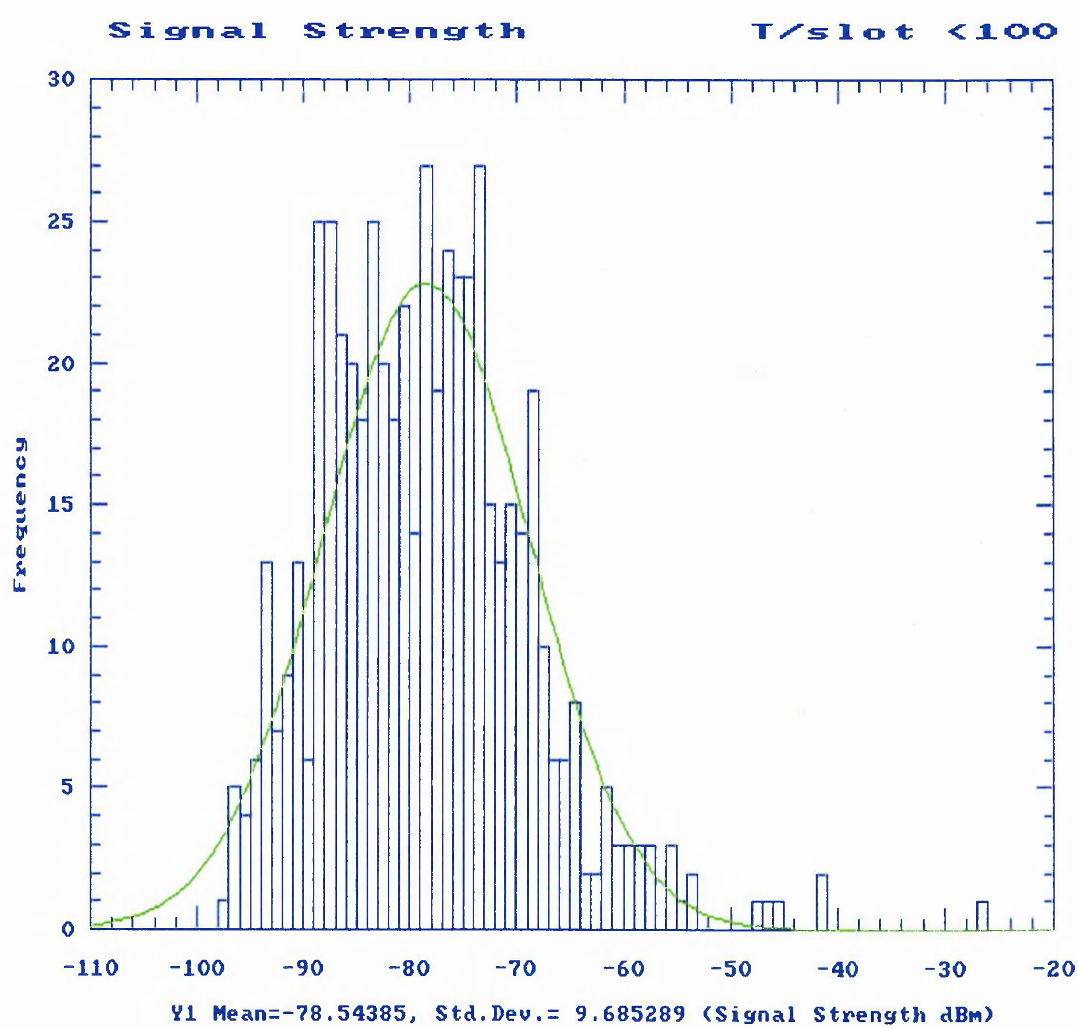


Figure 61 Distribution of Transponder Response for Time Slot < 100

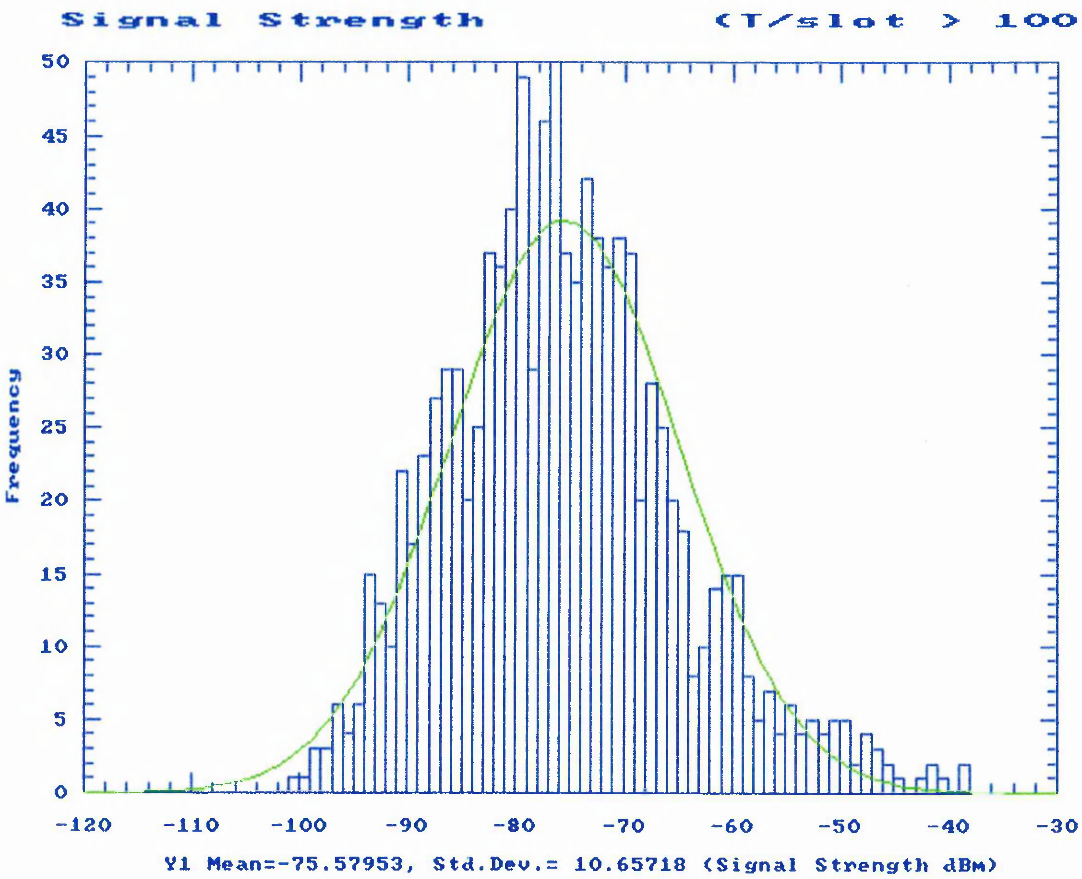


Figure 62 Distribution of Transponder Response for Time Slot > 100

To investigate whether the same transponders that responded only once or twice in 1st trial did the same in 2nd trial, the responses for 1st trial were plotted against the ones for 2nd trial. Most of the points in figure 63 are at or near the maximum. This shows that for the two sets of data it was a different set of transponders that responded only a few times. For 1st trial the maximum number of responses is 528 and for 2nd trial it is 288.

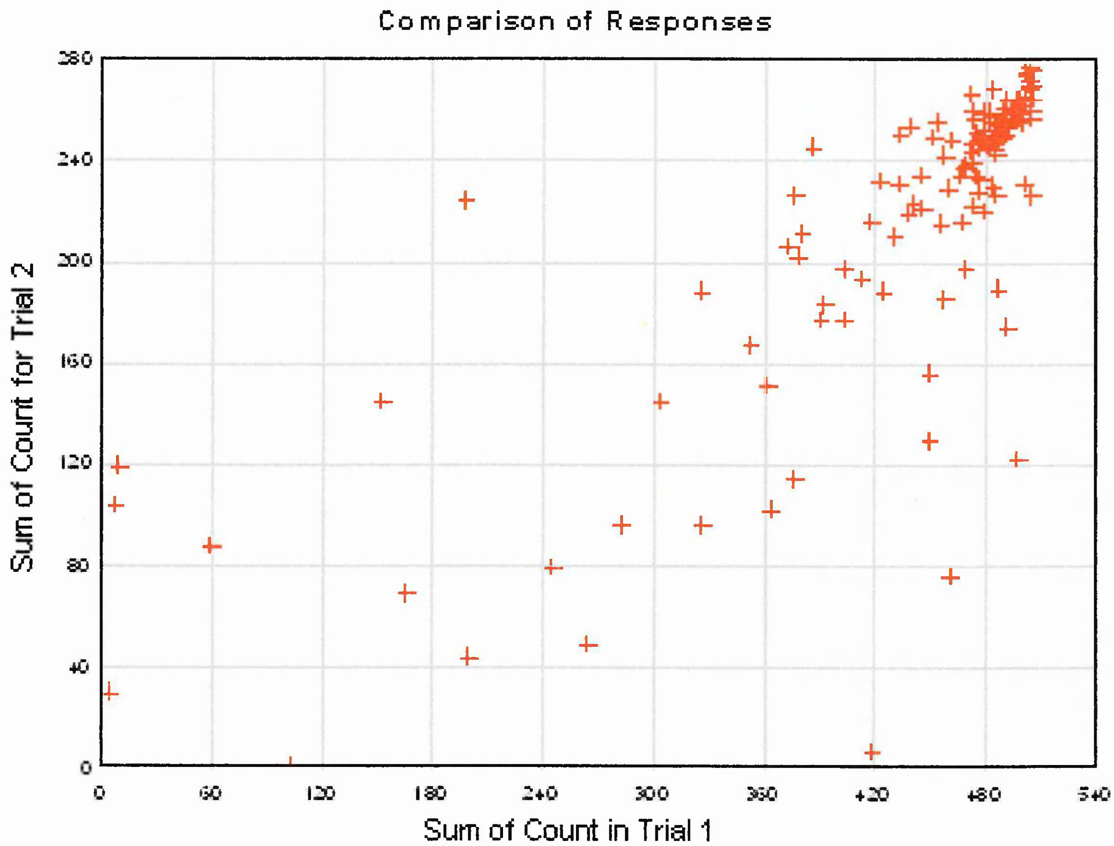


Figure 63 Transponder Responses Comparison 1st trial versus 2nd trial

6.3 Performance Analysis

The range and associated signal strength for each transponder was investigated. The position of each transponder has been plotted on maps of the area around each respective node. There is some evidence that some transponders are installed on less than ideal nodes. This is most evident on Queensway, as shown in figure 64 at ranges 600 to 750 metres and Parkside School, as shown in figure 67 at ranges 800 to 1000 metres, but can be seen on all nodes. This is due to installations of transponders taking place while the most appropriate node was unavailable for commissioning purposes. Future systems would incorporate a better automated configuration system that would reduce or eliminate these long propagation paths.

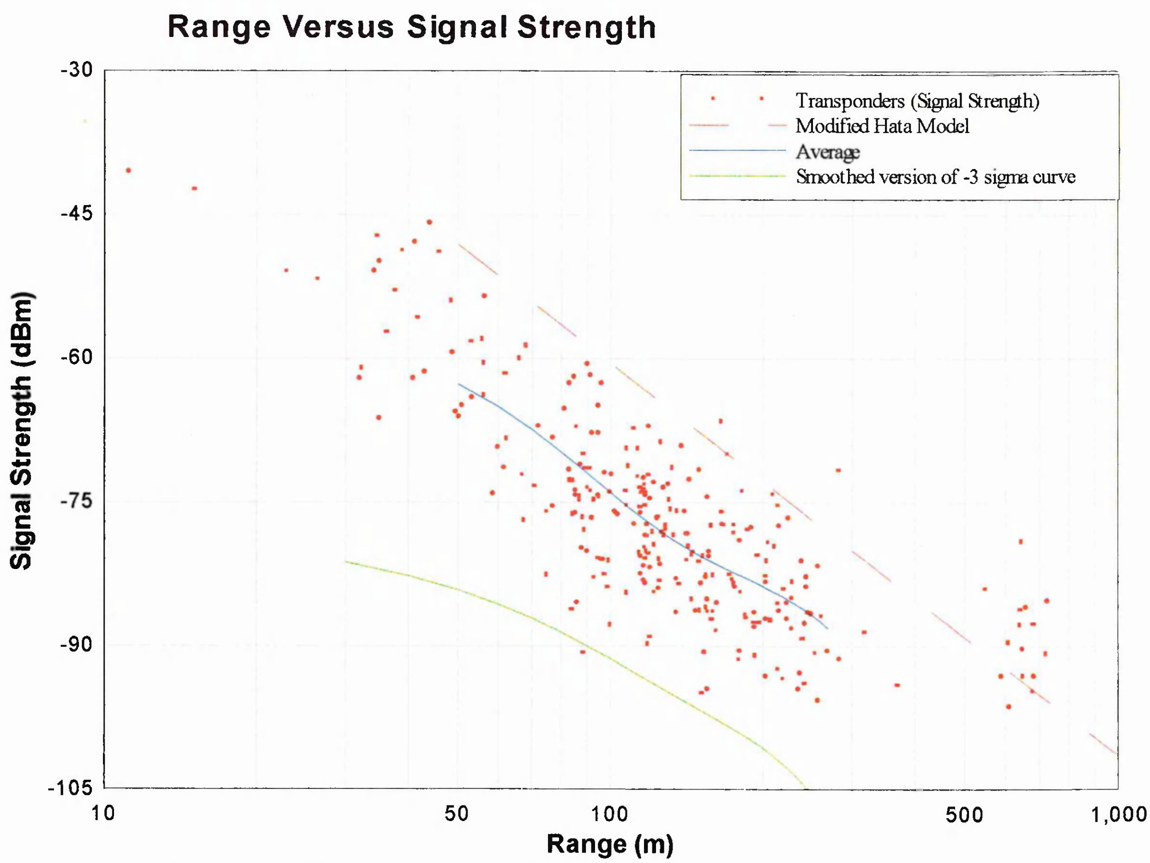


Figure 64 Range Versus Signal Strength Queensway Node

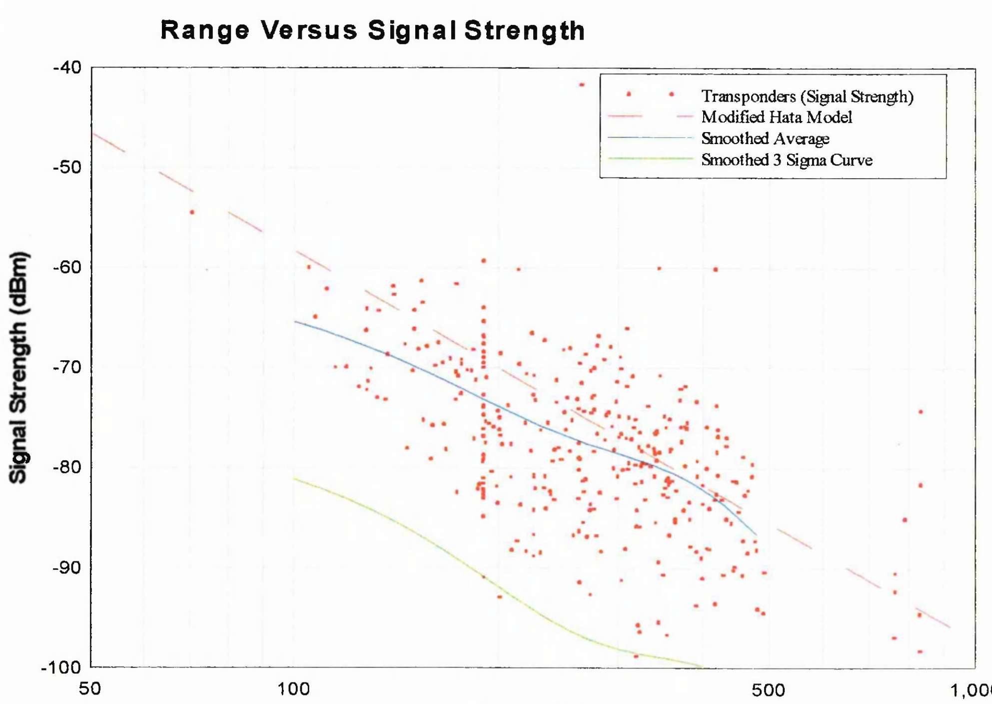


Figure 65 Range Versus Signal Strength Kingsway Node

For each node a plot of range versus signal strength was generated. Included on each plot is the modified Hata [11] model curve. This is a propagation prediction model derived from the original propagation studies by Okumura [9] et al made in Japan in the early 1970's. It predicts the mean path loss where 50% of the responses would be received. It is modified for frequency (184MHz), antenna height (node = 4 metres or 8 metres, transponder = 1 metre), and path loss into a building.

The path loss or insertion loss into a building can be anywhere from 3 to 38dB for a residential structure, see Skomal and Smith [12]. This is dependent on the type and construction of the wall and the distance the transponder is in from that wall, also any further obstructions encountered. Once inside the building the path loss is increased. Measurements made by RAMAR Technology suggest that a rule of thumb of 10dB provides a reasonable estimate in the first instance.

For each '10-metre' block of range on the graph the average signal strength and standard distribution were calculated. Two further lines were then added to each graph. One line is the smoothed version of the average signal strength. The other line is a smoothed version of the 3σ curve. This was calculated by multiplying the standard deviation of each 10-metre block by 3 and adding it to the average signal strength associated with that 10-metre block.

The production spread of CTS transponder transmit power, node receiver sensitivity and antenna gain and directivity will all affect the signal strength measurements plotted below. The variations in actual radiated transmit power due to transmitter power and antenna gain and directivity was +17dBm +/-5dB. The node receiver sensitivity variations were –105dBm +1dB/– 3dB. The node antennas were of two types, an end fed dipole giving omni-directional coverage and a Yagi antenna which gave 4dB gain over the dipole and a beam pattern of +/-36°.

Figures 64 to 69 show a variation in position and gradient of the average signal strength versus range curve for the transponders associated with a particular node when compared to the modified Hata model. The gradient of the modified Hata model at 40dB per decade was derived empirically from measurements made in an urban environment i.e. down town Tokyo by Okumura et al. The free field path loss is generally taken to be 20dB per decade. The height and density of buildings in the different areas of Goole will have less affect on the path loss thus the gradients will be between 20dB per decade and 40dB per decade. The measured gradients are listed in Table 8.

Node	Gradient (dB/Decade)
Queensway	35
Kingsway	27
Parkside	28
Woodlands	10 *
Prospect House	25
Pasture Road	24

Table 8 Gradient of average signal strength versus range

*Note, the gradient for the Woodlands node is small. No significance should be drawn from this result which is due to the small number of samples and the wide range of signal strengths.

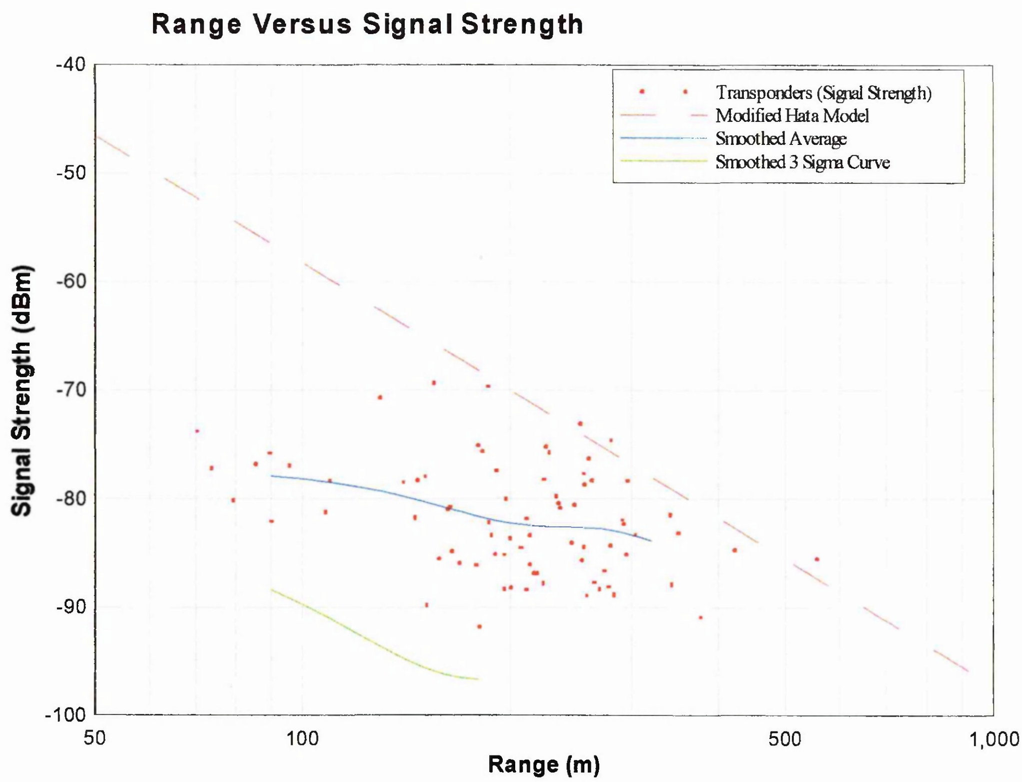


Figure 66 Range versus Signal Strength Woodlands Node

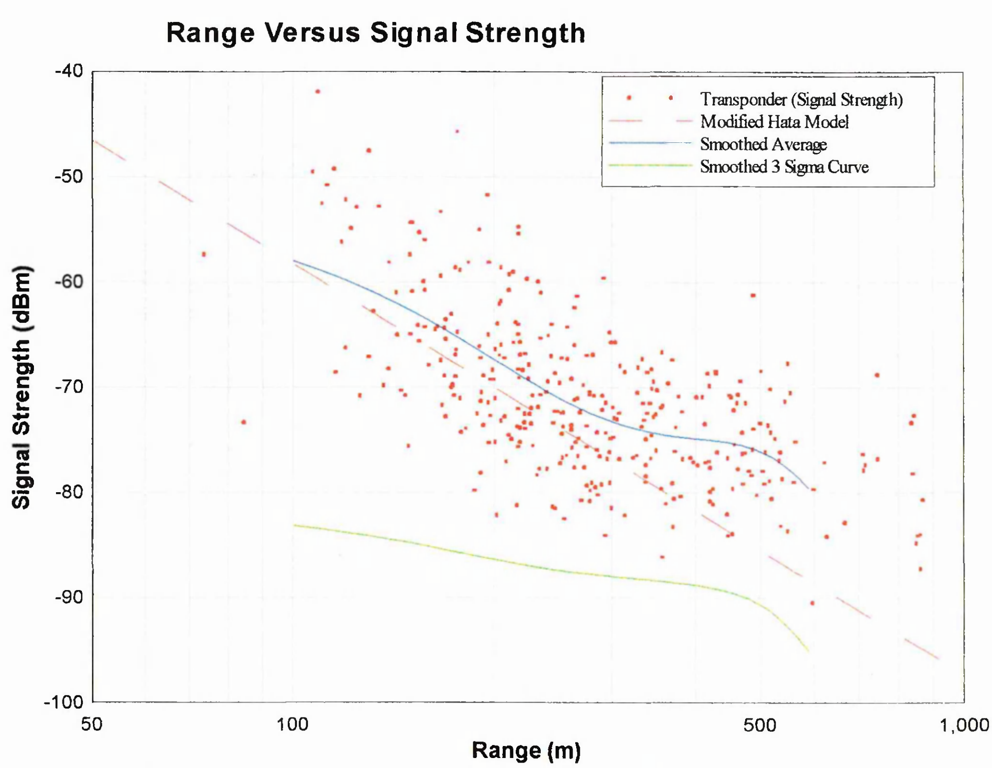


Figure 67 Range Versus Signal Strength Parkside Node

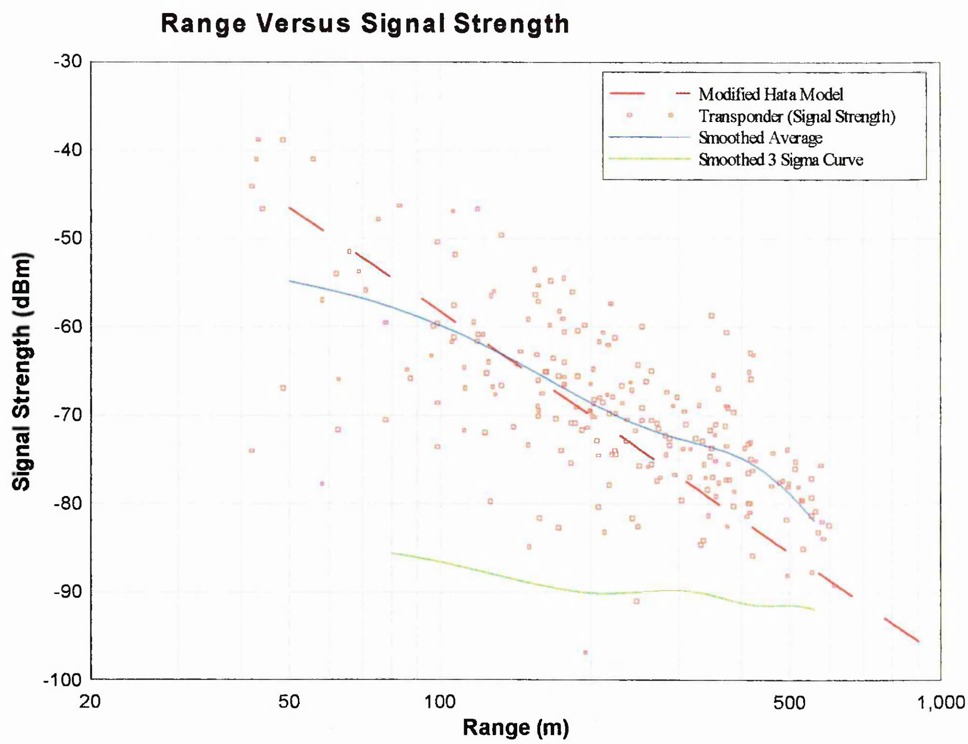


Figure 68 Range Versus Signal Strength Prospect House Node

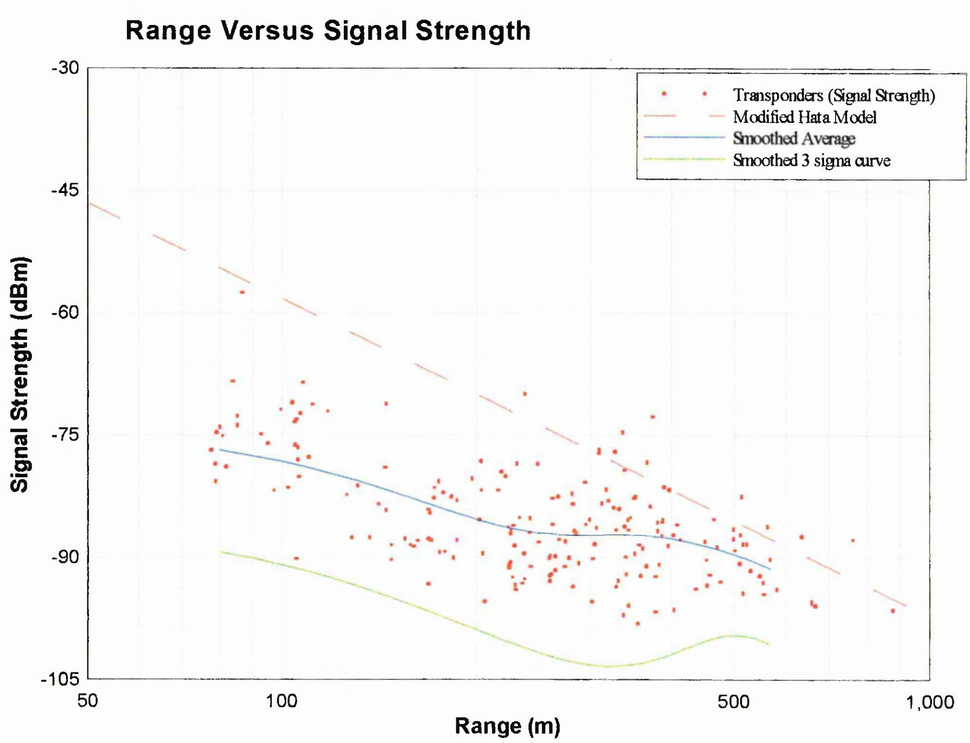


Figure 69 Range Versus Signal Strength Pasture Node

By projecting the smoothed 3σ curve so that it crosses the –100dBm Signal Strength level a predicted maximum range can be found. That range is listed in the table 9. Associated with that range and listed in Table 9 is the number of transponders, installed on that node, that are within the 3σ range.

Node	Node ID	Antenna Type	Antenna Height	Total Nos. of Transponders that responded	Range for 3σ > -100dBm	Transponders inside 3σ Range
Queensway	10	Dipole	4m	294	200m	220
Kingsway	11	Dipole	8m	330	330m	228
Parkside	14	Yagi	8m	77	500m	24
Woodlands	16	Dipole	8m	347	180m	306
Prospect	18	Yagi	8m	240	400m	194
Pasture Rd	20	Dipole	8m	207	300m	118

Table 9 Node Performance Statistics

There are two nodes whose 3σ range is much larger than the others. The performance of the Parkside School node and Prospect House, figures 70 and 53, show that the average signal strength of over ½ of the transponders are above the modified Hata model curve. The Yagi directional antennas have 4dB gain over the end fed dipoles used at the other nodes. This extra gain only goes part way to explaining the reduced path loss at these sites. The other effects that have some influence are the low densities of buildings in the surrounding area and some evidence of ducting especially at the Prospect House node, as shown in figure 53, figure 71, figure 72, and figure 73.

Figure 70 Parkside Primary School

Figure 71 Across from Parkside School showing the low roofs

Figure 72 Belverdere Crescent showing spaces between buildings and low roofs

Figure 73 Belverdere Crescent again showing the spaces between buildings and low roofs

The difference in signal strength for a given range was investigated for transponders installed inside a property and for those in external cabinets. The available data for the Queensway node was separated and plotted, as shown in figure 74.

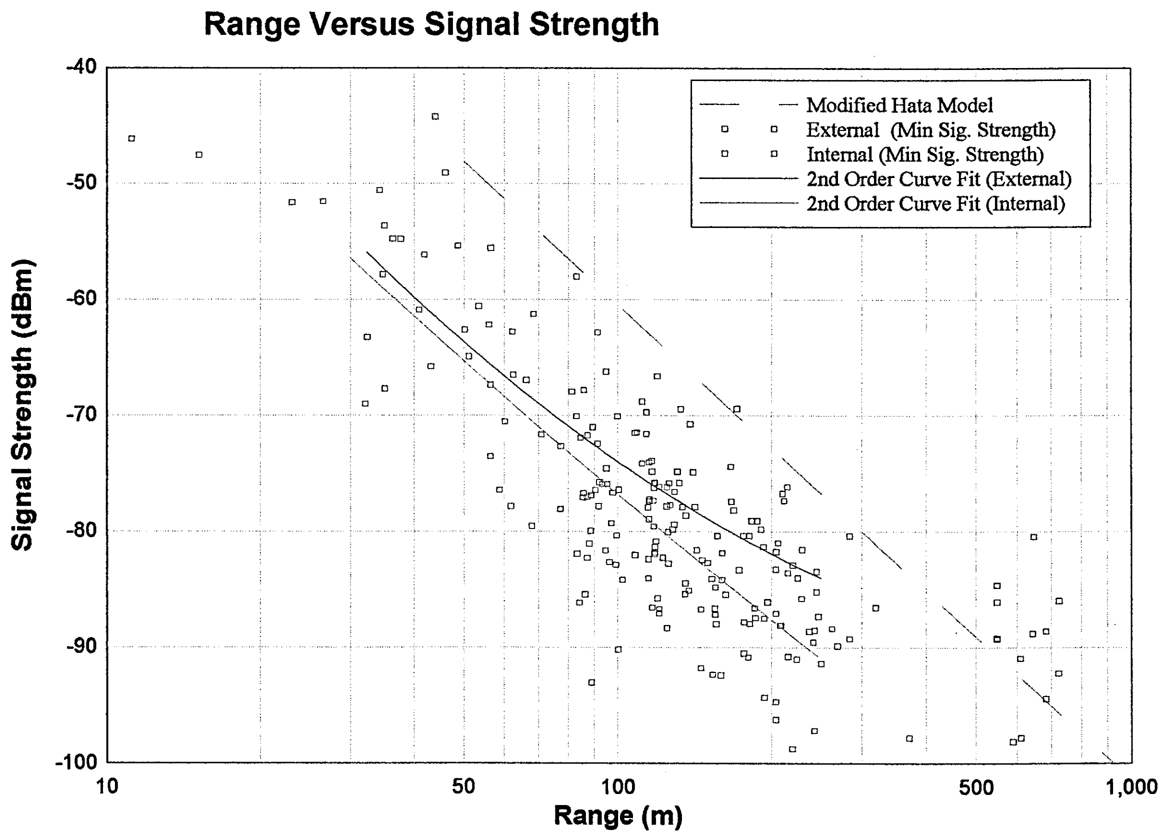


Figure 74 Range Indoors Versus Outdoors, Queensway node

The averaged curves in Figure 74 were generated by selecting the minimum signal strength recorded for each transponder during the 2nd trial period. The curve for the transponders that are installed inside is 3 to 5dB below the curve for the external transponders. This corresponds well with the minimum loss through a wall as predicted in Skomal and Smith [12]. The 3σ prediction of range will echo the variations shown by this data.

Note for the internal transponder signal strengths those transponders with the recorded meter locations "Hallway", "Internal" and "Front Room" was included. The recorded meter location "external cabinet" was used to separate the external transponders. No other corrections for the installation arrangement, direction or property type have been used.

Note that while not affecting the path loss prediction, antenna diversity may increase the transponder availability by reducing multipath effects. An effective retry strategy can have a similar effect.

6.4 CTS Propagation Analysis

The maps of the Queensway node, as shown in figure 77, and the Parkside node, as shown in figure 78 each show 3 contours of equal signal strength, at approximately -50dBm, -75dBm and -90dBm. These contours were generated by joining the transponders of similar signal strengths from the 'range versus signal strength' tables in the database. The active node is shown by blue square, other nodes that are on the same map show up as smaller blue squares.

The contours show the typical concentric circles of diminishing signal strengths that are modified by the surrounding geographical and structural environment. With reference to the map of the Queensway node the ranges to the majority of the transponders is small. There are some transponders at approximately 700 metres, which have signal strengths of –95dBm +/- 5dB. These are in the upper right hand corner of the map beyond Kingsway School. The propagation paths to these transponders are likely to include some ducting/wave guide effects in streets such as Kingsway as shown in figure 75 and Marshfield Avenue and then the open field path across the school grounds.

Figure 75 Kingsway

CRN	HOUSE NO.	STREET	HARD ID	SOFT ID	Location
6219017430	6	BROADWAY	1053	0000200A	Front room cupboard
6219018003	8	BROADWAY	1719	00002105	Front room cupboard
6219018832	10	BROADWAY	1602	00002067	Front room cupboard
6219019092	12	BROADWAY	1332	00002061	Front room cupboard
6219021212	16	BROADWAY	1668	0000207B	Front room cupboard
6219022043	18	BROADWAY	1801	00002063	Front room cupboard
6219023862	26	BROADWAY	1452	00002065	Front room cupboard
6219024441	28	BROADWAY	1469	00002062	External Cabinet
6219026002	32	BROADWAY	1450	00002066	External Cabinet
6219026831	34	BROADWAY	1438	00002068	External Cabinet
6219027660	36	BROADWAY	1377	0000206A	External Cabinet
6219029233	40	BROADWAY	1429	0000206B	External Cabinet
6219030043	42	BROADWAY	1445	0000400C	External Cabinet
6219030872	45	BROADWAY	3149		Kitchen Cupboard
6219033270	39	BROADWAY	1474	00002071	External Cabinet
6219034003	37	BROADWAY	1358		External Cabinet
6219059672	16	QUEENSWAY	1879	0000209A	Front Room
6219060492	18	QUEENSWAY	1749	0000209C	Front Room
6219062050	22	QUEENSWAY	1790	000020A3	Front Room
6219063204	26	QUEENSWAY	2991		Front Room
6219063612	28	QUEENSWAY	1945	0000209D	External Cabinet
6219064452	30	QUEENSWAY	1588	000020AF	Front Room
6219065281	32	QUEENSWAY	3277		Front Room
6219066011	34	QUEENSWAY	2355	00002116	Front Room
6219074841	61	QUEENSWAY	2131	000020B0	Under Staircase
6219075673	59	QUEENSWAY	2173	000020BB	Under Staircase
6219075833	57	QUEENSWAY	1889	000020B9	Front Room

Table 10 Example of Transponder Location

The Queensway site, signal strengths plotted in figure 77 is interesting, the housing density in the area surrounding the node is high, the streets being mostly terraced, as shown in figure 76 and the antenna height is low (4 metres); that is well below the heights of the surrounding roofs. This will reduce the range to the majority of transponders but will increase the ducting effects. Figure 56 and 57 show the antennas mounted below the surrounding roofs.

Figure 76 Queensway

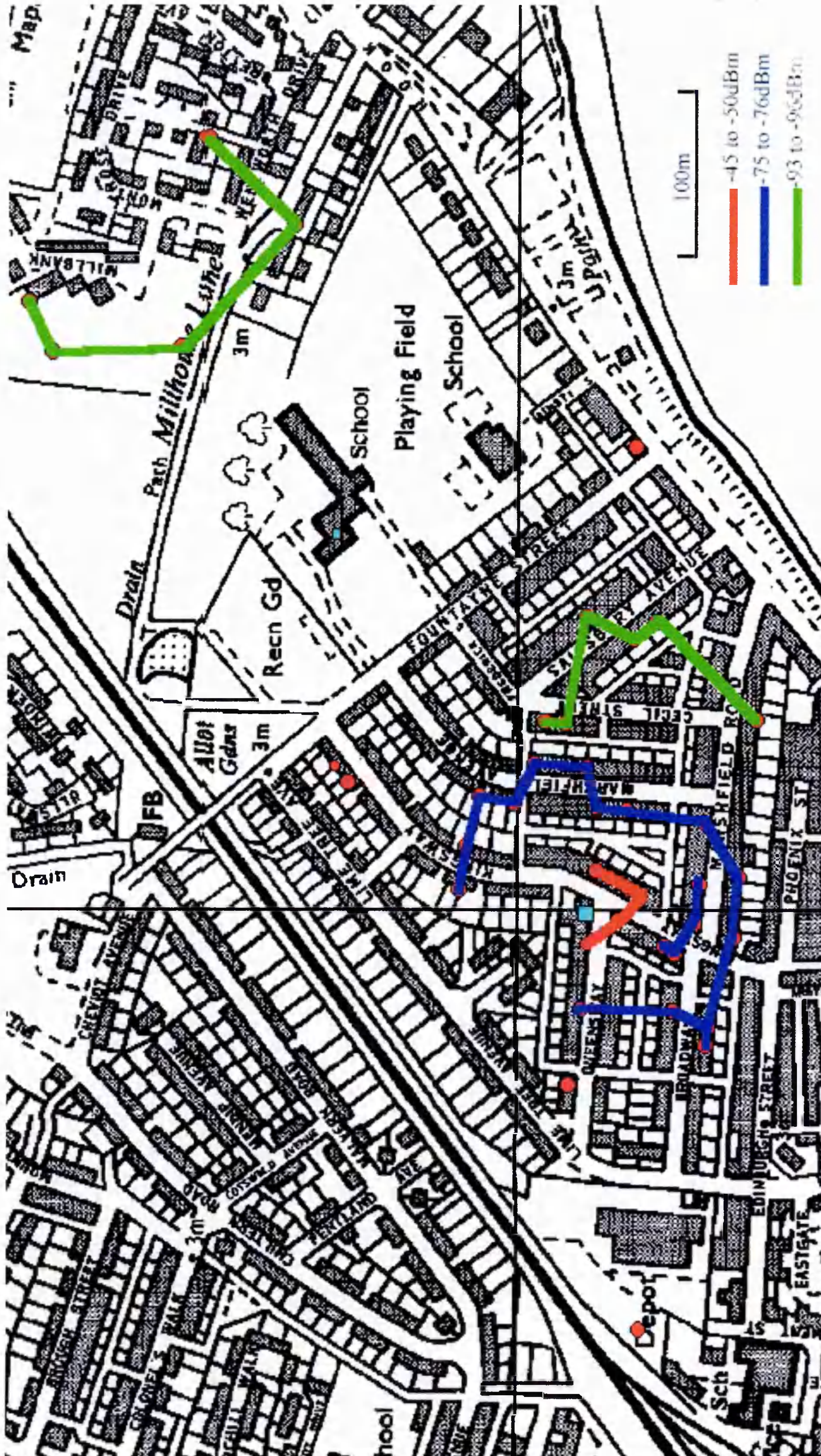


Figure 77 Queensway Signal Strength Contour Map

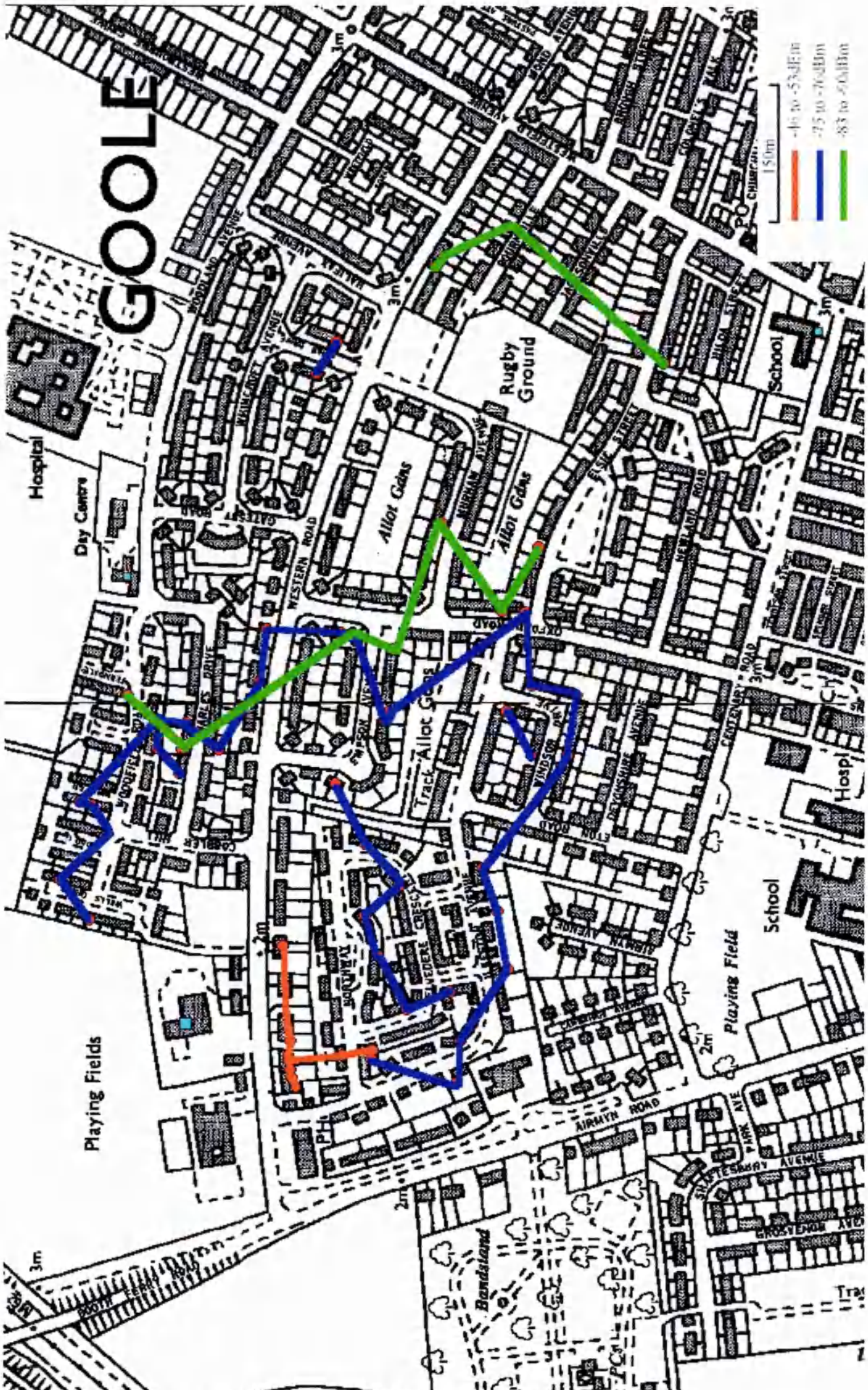


Figure 78 Parkside Signal Strength Contour Map

Figure 78 is a map for the Parkside School node. This site has 2 Yagi type antennas mounted at a height of 8 metres. The signal strength contours reproduce a beam pattern for a Yagi Antenna well. The propagation path is conducive to good ranges, as the first obstructions are well-spaced single story buildings a good distance away. This reflects in the extended 3σ range listed in Table 11.

Analysis of the plots of signal strength versus range, shown in figures 66 to 69, shows that the Modified Hata Model can be used to predict the range when applied to a site with omni-directional antennas. For sites with Yagi antennas the model is pessimistic. Figures 79 to 84 show the node site for each of the 6 nodes, with the node represented as a blue dot and that node's corresponding transponders as round purple dots. The red dots are transponders that did not respond during that specific ½ hourly interrogation sequence.

To predict the range at which 99% of transponders will respond every time an attenuation factor must be added to the Modified Hata Model, the measured attenuation factors are listed in Table 11. Choosing squares on the appropriate map and counting the number of houses inside derives an average housing density figure. The difference in attenuation factor between the Queensway and Kingsway nodes that service houses in the same area can be explained by the difference in antenna heights and the lack of clutter around the Kingsway node.

Node	Attenuation Factor	Housing Density
Queensway	-30dB	48
Kingsway	-22dB	48
Woodlands	-30dB	32
Pasture Road	-32dB	54

Table 11 Attenuation Factors for the Modified Hata Model

6.5 Conclusions

There are several competing technologies either available now or soon to be available that will enable Utilities to gather up to date information cheaply and reliably. The choice breaks down to two main areas, data gathering system owned and operated by the Utility versus sub-contracted out with perhaps leased lines or leased radio links as well as which medium the data should be transmitted over. The transmit medium for an AMR system has at the moment four competing transmission mediums, telephone, cable, PLC and wireless. All of these transmit mediums are at different stages of evolution with PLC perhaps the least advanced at the present time.

Wireless offers the most flexible system in that it can be owned and operated by the Utility or by a sub-contractor. It can usually be retrofitted with little disturbance to the customer. The installation can be as small or as large as is required given proper network planning. While PLC is in its infancy it may be retrofitted quickly and cheaply especially a narrow band low data rate system dedicated to gathering meter readings.

The cost of installing the wireless data gathering system will be dependent on the level of control and complexity required. Simple systems to gather meter readings on perhaps a daily basis require a simplex or one way link. More complex two-way links that offer the Utility some degree of control over their network or value added service to the customers more than double the complexity of the system. Predicting the coverage within a cell for a given radio system is key to minimising the costs by not installing more nodes than are necessary. Where the coverage is patchy or non-existent will require other methods of data gathering that may not be so efficient in terms of freshness and accuracy of data or cost.

The costs mentioned above should be balanced against the costs of leased lines or other data gathering mediums. Where data from several meters such as gas, water and electricity meters can be transmitted over the same system, with no overload of the transmit medium, this is more cost efficient than under utilising the transmission medium.

- A radio system at 184MHz for reading utility meters on a 30 minutes basis is viable.
- A low data rate PLC system is viable and may be easily retrofitted.
- Antenna positioning and especially height is important.
- Directional and gain antennas for instance a Yagi can in some circumstances increase the coverage.
- The site survey and node position is critical to achieving good coverage.
- The modified Hata model with suitable attenuation factors can be used to predict coverage.
- Predictions of coverage should be modified when internal or external installation of transponders is contemplated.
- Minimum detectable signal (MDS) of the RAMAR Technology CTS system as deployed in Goole is -100dBm.
- The similarity of the distribution of the responses for timeslots above and below 100 supports the use of all data when generating the range versus signal strength plots and the propagation models.

The inclusion on an automatic system configuration module will ensure transponders are configured on the most suitable node.

Figure 79 Queensway Node and Associated Transponders

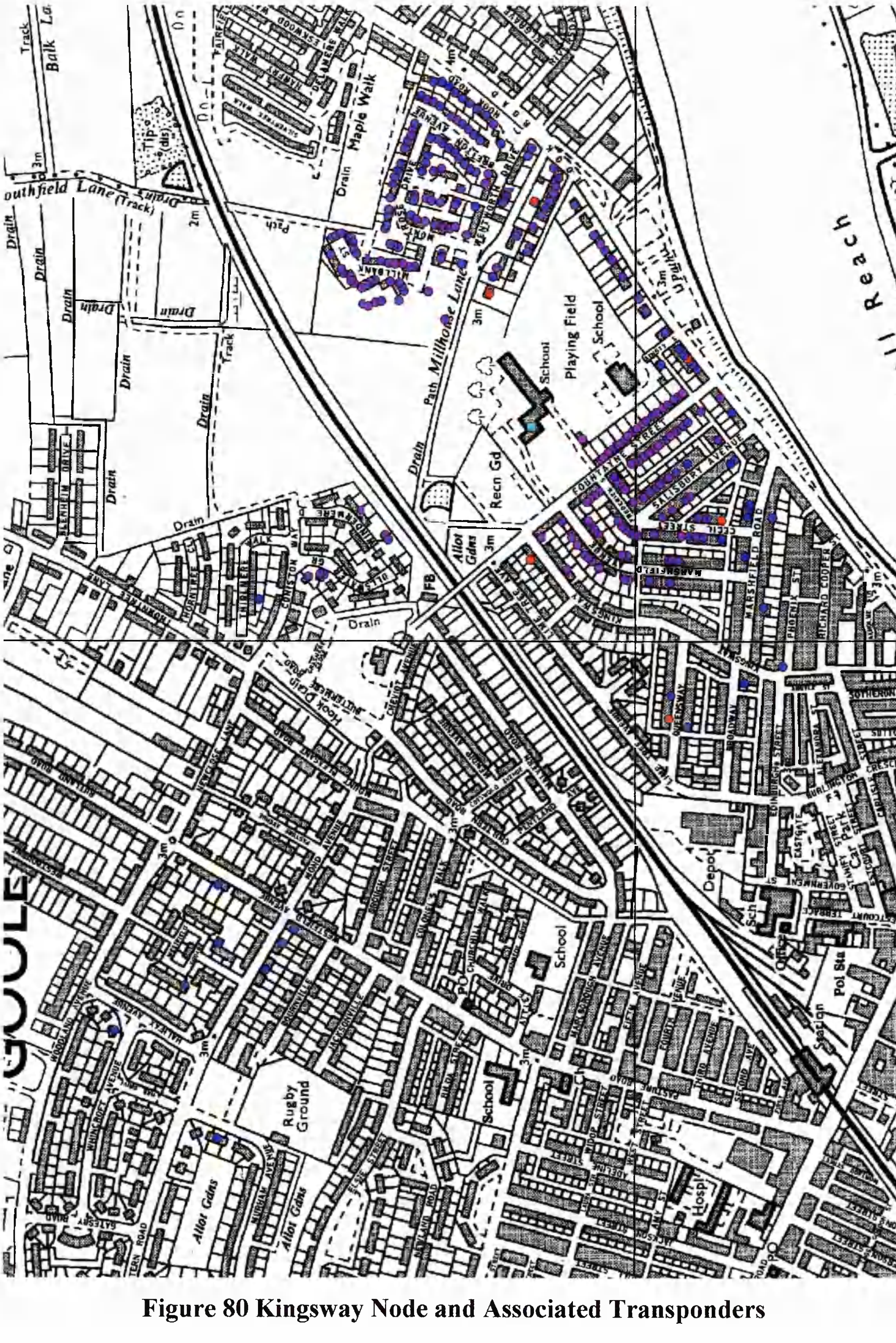


Figure 80 Kingsway Node and Associated Transponders

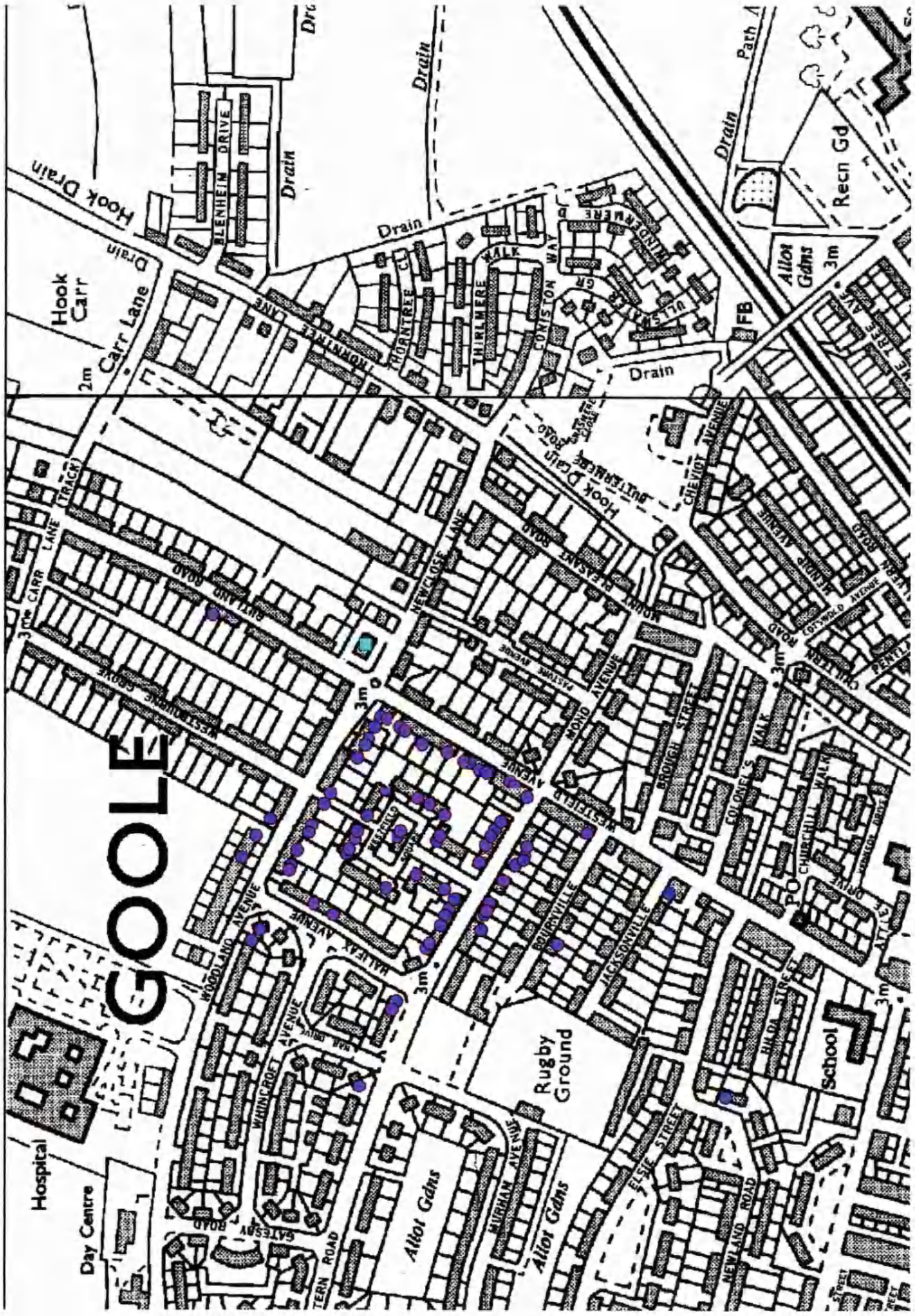


Figure 81 Woodlands Node and Associated Transponders

Figure 82 Parkside Node and Associated Transponders

Figure 83 Prospect House Node and Associated Transponders

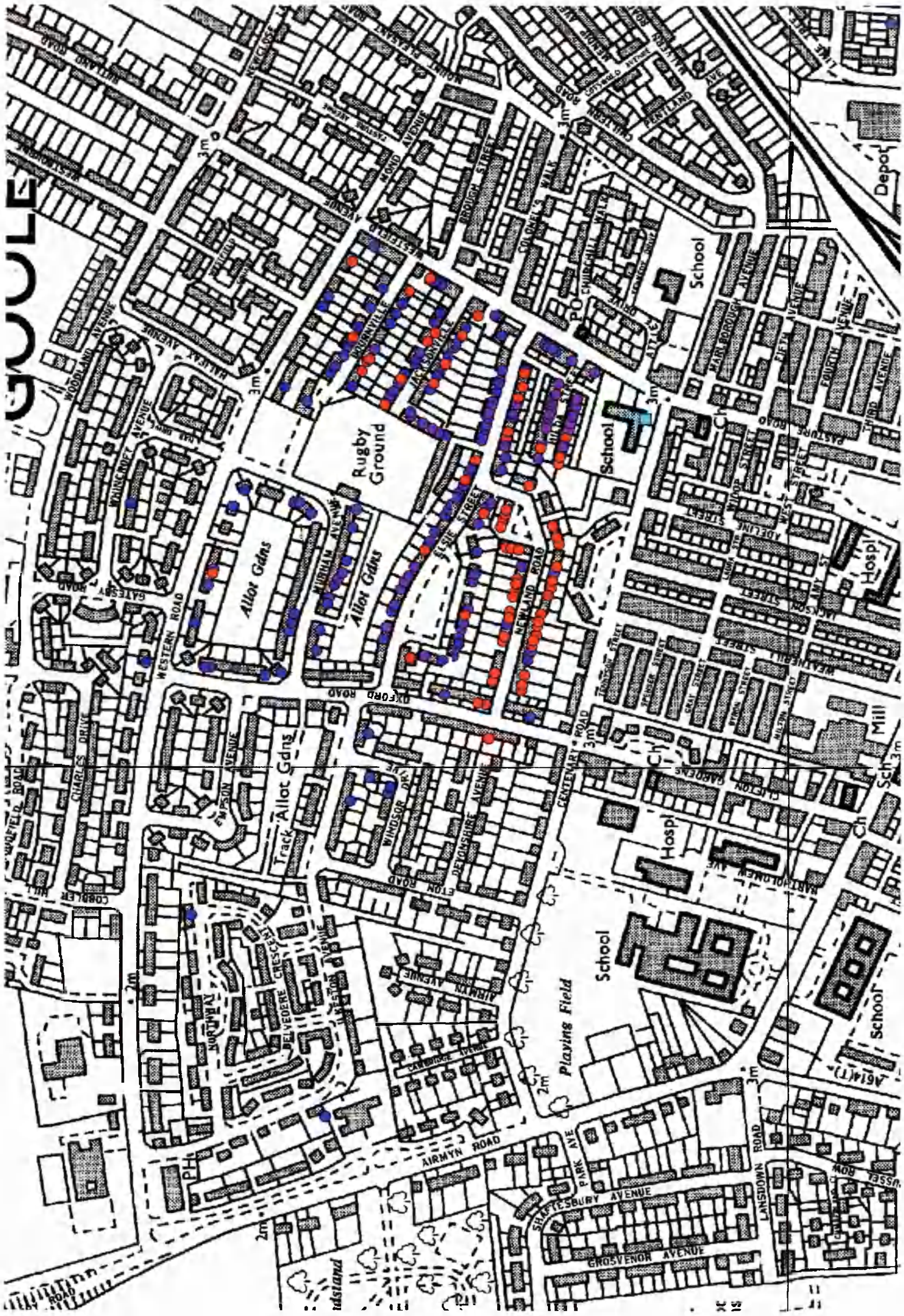


Figure 84 Pasture Road Node and Associated Transponders

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List of Figures and Tables

Abbreviations and Symbols

Moving Pictures Experts Group 2 (MPEG2) = 2 – 4MBPS

Digital Video Disc (DVD) = 3 – 8MBPS

High definition Television (HDTV) = 14MBPS

ADSL .... Asymmetric Digital Subscriber Line

AMR .... Automated Meter Reading

BER ....Bit Error Rate

BPL ....Broadband Power Line

BPSK .... Binary Phase Shift Keying

CATV.................Cable Television

CISPR .... Comité Internationale Spécial des Perturbations Radioelectrotechnique (International Special Committee on Radio Interference, IEC)

DFSK .... Digital Frequency Shift Keying

EMC ....Electro-Magnetic Compatibility

EMF ....Electromotive force

EPU ....Enforcement Policy Unit, part of the RA

FER ....Frame Error Rate

GMSK .... Gaussian minimum Shift Keying

HAP ....House Access Point

IEC ....International Electrotechnical Commission

ISI ....Inter symbol interference

LAN ....Local area network

LOS ....Line of Sight

LV .... Low voltage (230 Volts AC single phase)

MCU ....Microprocessor Control Unit

MDS ....Minimum detectable signal

MSK ....Minimum Shift Keying

NIC ....PC Network Interface Card

NLOS ....Non line of sight

QoS ....Quality of service

OFDM ....Orthogonal Frequency Division Multiplexing

PAPR .... Peak to Average Power Ratio

PHY .... Physical Layer

PIZ .... Public Information Zone

PLC ....Power line carrier

PLM .... Power Line Modem

PLT ....Power line technology

POTS ....Plain Old Telephone System

PSD .... Power Spectral Density

RA .... Radio Communications Agency, UK government department responsible for the radio spectrum

SIMM ....Single Inline Memory Module

SMS ....Short Message Service

SSI ....Signal Strength Indicator

SOHO .... Small Office Home Office

TBF ....To be Filled

TDMA ………………Time Division Multiple Access

TEM …………………Transverse Electromagnetic wave

TWG …………………Technical Working Group

WAN ………………. Wide area network

UK ………………….. United Kingdom

UTP …………………. copper twisted pair

YEG …………………Yorkshire Electricity Group

λ = wavelength

$\mu = \mu_o \times \mu_r$ = permeability

μ_r = relative permeability of a material

μ_o =permeability of free space = $4\pi \times 10^{-7}$ H/m

$\varepsilon = \varepsilon_o \times \varepsilon_r$ = permittivity

ε_r = relative permittivity of a material

ε_o = permittivity of free space = 8.854×10^{-12} farads/metre

σ = conductivity in mhos

ρ = charge density.

APPENDIX 1 Nimbus Test measurement system

It was decided to construct a mains coupling filter using the same components as those used in the ST Demo Board. This filter was plugged into the mains and an oscilloscope used to monitor the noise and signal on the line.

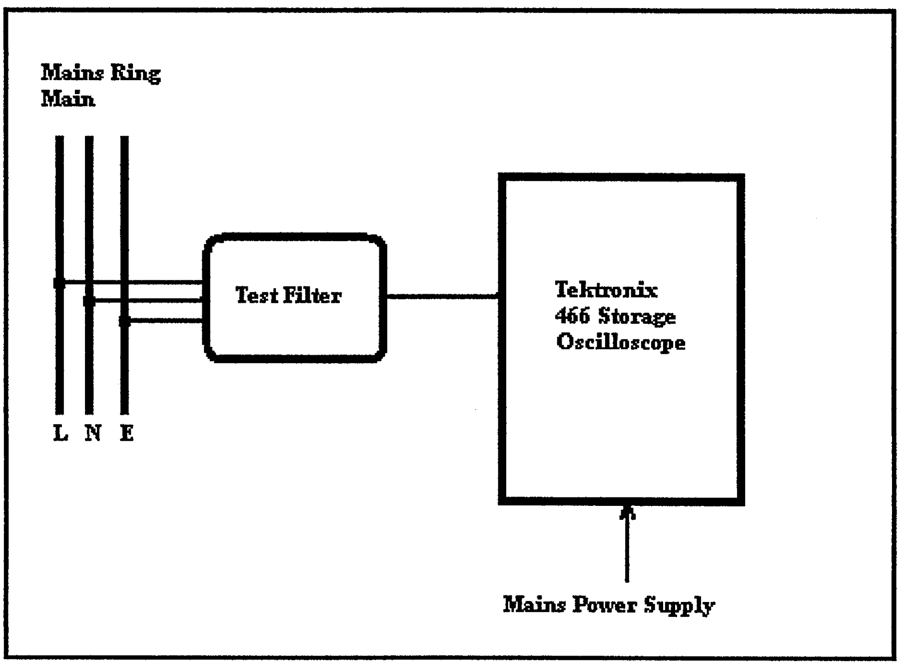


Figure A1.1 Test Measurement Block Diagram

The test filter was modelled using PSpice and the representative filter circuit given in the ST Application note AN1714.

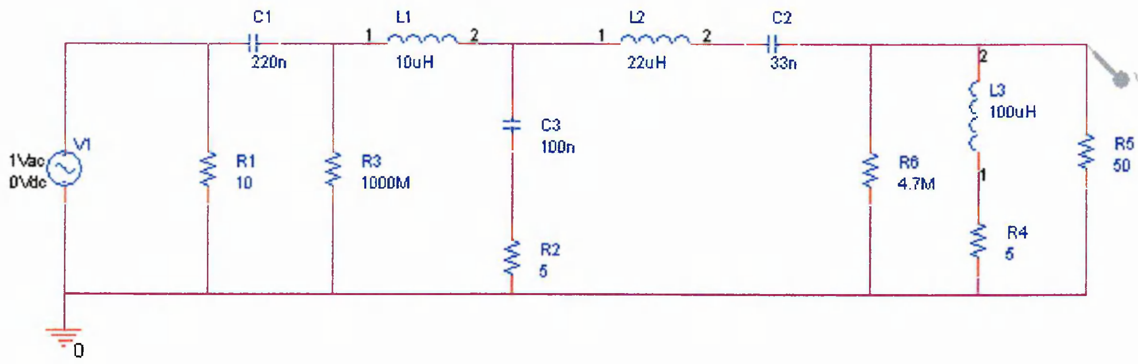


Figure A1.2 PSpice Schematic

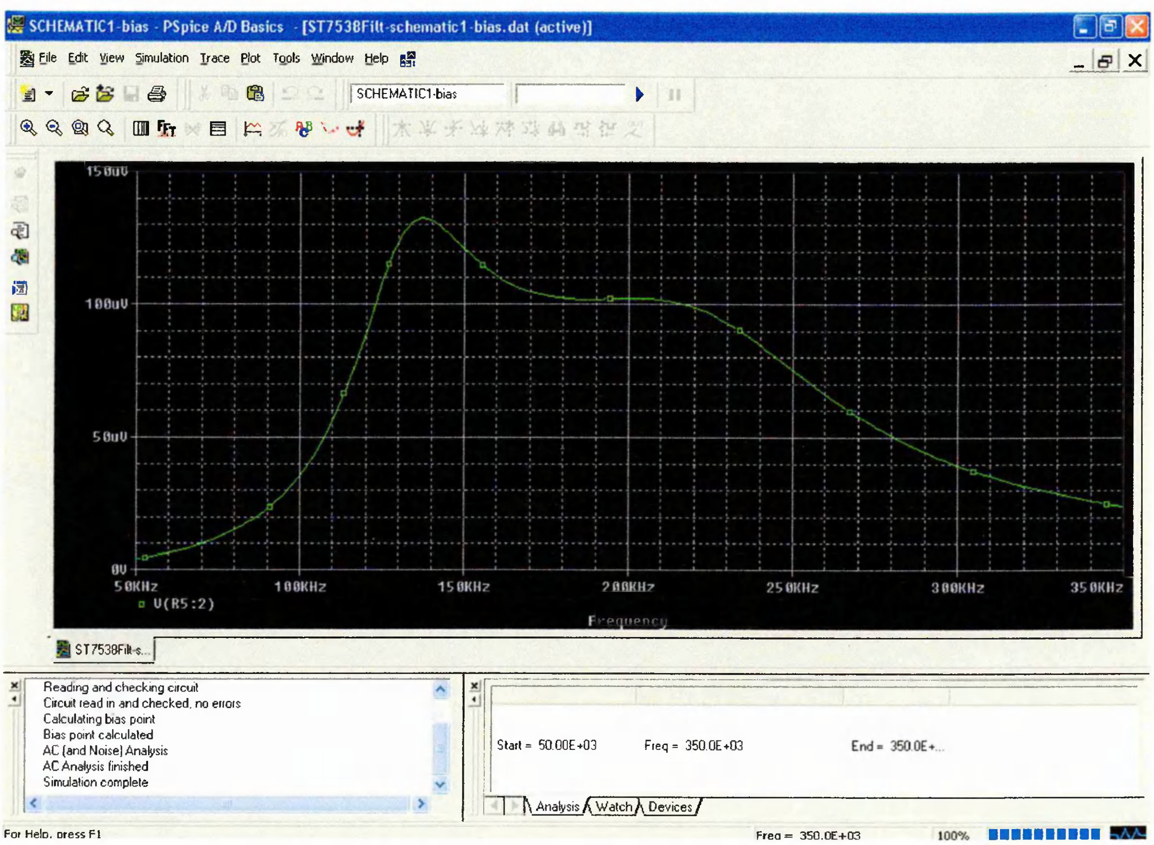


Figure A1 .3 Pspice output graph

The Filter was then characterised by injecting an AC signal maintained at 1 volt peak to peak into the filter and the output measured across the Artificial network (CISPR 16-1). The results are shown table A1.4.

Test Frequency (kHz)	Output Voltage (Volts p-p)	Gain (dB)
26	0.15	-16.5
40.7	0.25	-12
50.4	0.3	-10.5
70	0.55	-5.2
79	0.7	-3
90.2	1	0
100	1.4	2.9
108.5	1.7	4.6
120.8	1.55	3.8
130	1.5	3.5
152.2	1.2	1.6
185.4	1.17	1.4
207.6	1	0
230.6	0.8	-1.9
261.2	0.58	-4.7
295.1	0.34	-9.4
332.3	0.08	-22

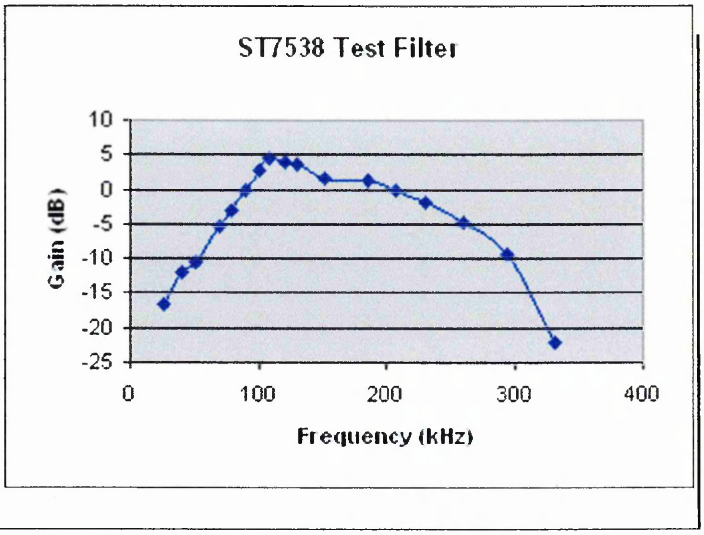


Figure A1.4

It can be seen from the results above that the actual circuit is exhibiting voltage gain. This must be due to the loading on the filter and it may be the artificial network is not adequate for this trial.

The filter was then tested in the other direction that is with the signal injected at the mains side (not connected to the mains) and the signal measured on the ST7538 side. The ST7538 was emulated by a 10 ohm resistor which is considered to be close to the output impedance of the TX stage.

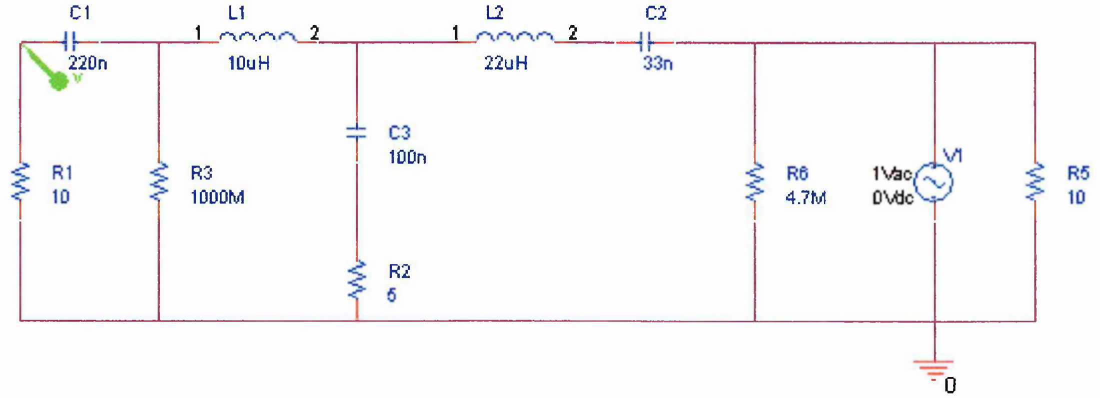


Figure A1.5 PSpice Schematic 2

Note that resistor R5 was used to emulate the mains. This circuit was modelled and the results shown in figure A1.6.

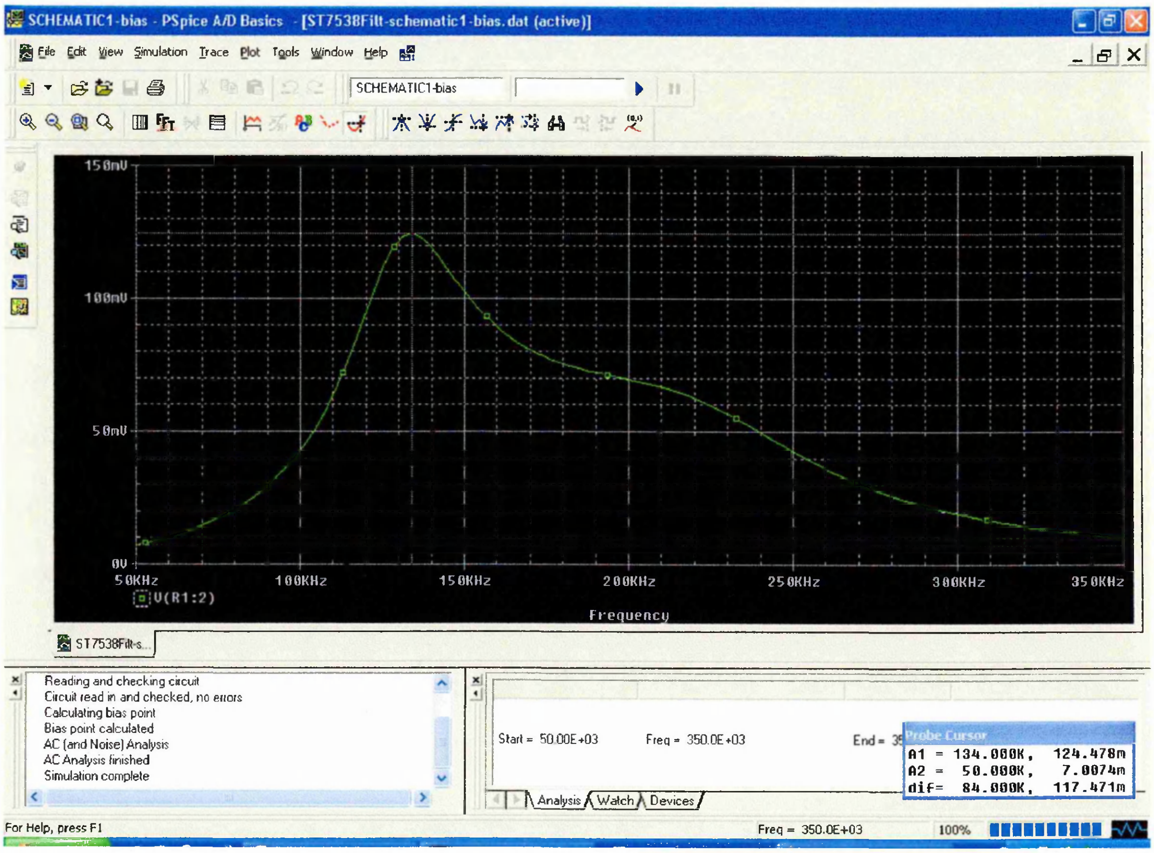


Figure A1.6 Simulated TX filter pass band (signal injected in mains side)

This circuit was also characterised as before with the AC signal maintained at 1 volt p-p.

ST7538 Test Filter 1 volt p-p AC signal injected from mains side

Frequency (kHz)	Output Voltage (volts p-p)	Gain (dB)
18.8	0.033	-29.6
30.2	0.046	-26.7
41	0.064	-23.9
51.5	0.086	-21.3
63.6	0.11	-19.2
73.6	0.145	-16.8
85.3	0.175	-15.1
95.1	0.2	-14
108.3	0.23	-12.8
115.4	0.3	-10.5
125	0.37	-8.6
133.8	0.45	-6.9
144.9	0.56	-5
159.2	0.63	-4
169.6	0.598	-4.5
181.3	0.45	-6.9
192.2	0.39	-8.2
222.2	0.25	-12
239	0.17	-15.4
252.4	0.16	-15.9
265.6	0.13	-17.7
291.6	0.1	-20
310.3	0.08	-21.9
346.5	0.06	-24.4
386.4	0.042	-27.5
407.8	0.038	-28.4

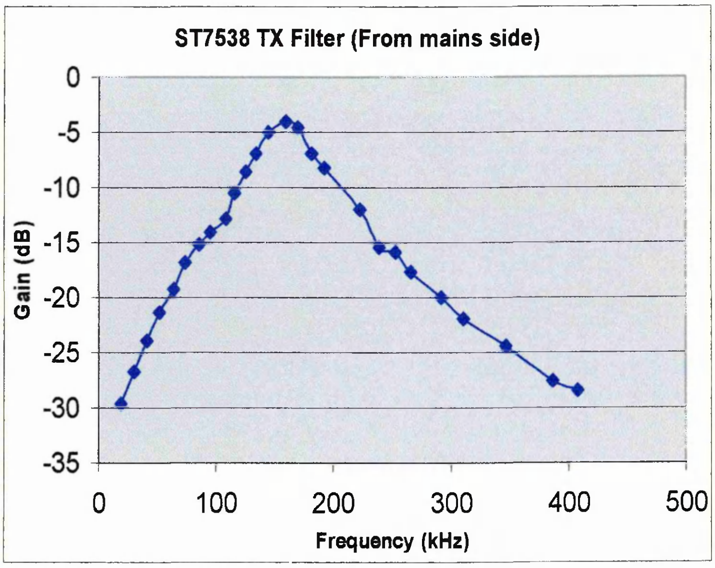


Figure A1.7

This is a more believable result and closer to the actual usage of the filter circuit so it will be used in future trials.

APPENDIX 2 Meteorological Nomenclature

Troposphere (ground to 10km)

Low clouds up to 2km, medium clouds to 4km, high clouds to 10km, aircraft at 15km

Temperature decreases with height until tropopause where temperature starts to increase.

Temperature at the tropopause is approximately -50°C.

The varying refractive index of air is what affects the radio waves and is dependant on time of day, weather and latitude and other factors; the effect is usually at about 2-5 km in height.

Stratosphere (10km to 50km)

Ozone layer at 20km

Mesosphere (50km to 80km)

Thermosphere (80km to 1000km)

Temperatures up to 1200°C

Ionosphere (60km to 700km)

APPENDIX 3 Yorkshire Electricity Group PLC RADIO SPECIFICATIONS

The radio specification describes the layers 1 and 2 of the CCITT OSI 7 layer model that is the Physical Layer, covering the radio characteristics, and the data link layer describing the data exchange over the radio link to be used in the Yorkshire Electricity Group PLC 184MHz AMR system.

The physical layer aspects of this specification are intended to meet the generic European Radio Specification ETSI 300-220 as amended by the DTI RA TDS MPT1601 V2 August 1997(that is the 100mW EIRP version).

There are two main parts to the AMR system, the first part is the node which is at a fixed point and communicates with the electricity meters by radio and to the outside world by some type of modem, either radio or PSTN, providing a wide area network connection (WAN). The meter has a transmitter and receiver for communicating to the node by what is normally described as a radio local area network (LAN).

The system will be capable of working in a number of ways these include:-

a) Wakeup from the node to all the meters within range with a request for an index or group of indexes.
b) A request from the node to a single or group of meters.
c) A broadcast from the node to the meters for example to update their clocks.
d) An exception message from a meter to the node to report unusual events such as power failure or tampering.

e) A command sequence from the node to a particular meter to perform a function such as consumer power disconnections, software update. The system should also be capable of sending control messages to switchgear.

f) Later implementations of the meter hardware will also allow them to operate as repeaters permitting a water meter transponder to pass through the electricity meter to the node and hence onto the WAN.

The mode a) above will use the normal RAMAR data collision strategy modified to cope with the longer data packets, see the data link layer section 3.

The forward or wakeup path will use relatively slow direct frequency shift keying (DFSK) at 1kbps data rate. The responses will be sent using MSK at a data rate of 100kbps. Both paths will be designed to fit within one 200 kHz wide band channel as defined by the RA in DTI specification MPT1601.

MSK modulation is proposed because this is essentially constant amplitude and so will allow a class C power amplifier for maximum efficiency. Also the node receiver IF amplifier can be a limiting type as opposed a more complex automatic gain controlled type needed for simple QPSK or BPSK.

A3.1 System Performance

The cost effectiveness of any fixed network AMR system is a function of the number of meters per node which is mainly determined by the radio range. There is a good business case for a fixed network AMR system if the Node can support more than 100electricity meters. This should be easy to achieve in urban areas.

An arbitrary urban range for the system between the node and the meters is defined as ½ mile (750m) and the link budget calculations for this range have been shown in paragraph 5.9.2 page 102.

This specification was only intended to cover the radio hardware and the over the air data as covered by layers 1 and 2 of the OSI model. The data throughput and access time to a given meter, of the full system was dependant on the WAN performance and so was outside the scope of this thesis.

A3.2 Layer 1 -Physical Electrical Specification

Characteristic	*Min*	*Typical*	*Max*	*Unit*
Operating Temperature Range	-25	20	60	°C
Storage Temperature Range	-60	-	+100	°C
Supply voltage -meter		5		V
DC Current - meter (radio system only)		25	100	mA
Supply voltage - node		12		V
DC current - node (radio inc DSP)			500	mA

A3.3 Forward Path Node Transmitter

This transmitter was a simple crystal oscillator and multiplier type with direct modulation applied to a variable reactance on the crystal. The modulation used will be direct frequency shift keying (DFSK) and the data will be differentially Manchester encoded.

All characteristics are over the full temperature range, -25 to +60°C, unless otherwise noted.

Characteristic	*Min*	*Typical.*	*Max*	*Unit*
Transmit frequency		184.000		MHz
Carrier frequency error		0	5	kHz
DFSK deviation	+/- 1	+/-2	+/-3	kHz
Bit rate (differential Manchester encoding)		1		kbps
Output power - conducted (50 Ω)	150		250	mW
Output Power - radiated (EIRP)	70		100	mW
Spurious emissions to meet ETSI 300-220		-54		dBm
Channel bandwidth		25	200	kHz
Start up time on to frequency		2	5	mS
Transmit enable time to full output power after start up time		100	200	uS
Current consumption peak at 5V			100	mA

A3.4 Forward Path Meter Receiver

This receiver could be implemented in a number of ways including direct conversion pager type receivers, offset IF or a conventional double conversion receiver and in fact a single conversion superhetrodyne receiver was utilised. A crystal oscillator was chosen so that the when mixed with the received RF it gave an IF of 10.7MHz and when mixed with the transmit signal it gave the correct 184MHz transmit signal.

All characteristics are over the full temperature range , -25 to +60°C, unless otherwise noted.

Characteristic	*Min*	*Typical*	*Max*	*Unit*
Receive centre frequency		184.000		MHz
Receive frequency error		0	5	kHz
DFSK deviation	+/- 1	+/-2	+/-3	kHz
Bit rate (differential manchester encoding)		1		kbps
Sensitivity for 1 in 10^5 BER (10 dB SNR)			-118	dBm
Image rejection	70			dB
IF rejection	70			dB
Bandwidth		15		kHz
Current consumption at 5V		25		mA

A3.5 Response Path Meter Transmitter

This transmitter needs to generate MSK modulation and the data will be preconditioned with appropriate timing and filtering to give minimum shift keying (MSK). It is likely that in order to reduce the spurious components after the modulator it will need to be a at least a single conversion transmitter. The necessary filtering could be obtained by a low cost 10.7MHz FM radio filter.

All characteristics are over the full temperature range , -25 to +60°C, unless otherwise noted.

Characteristic	*Min*	*Typical.*	*Max*	*Unit*
Transmit frequency		184.000		MHz
Carrier frequency error		0	+/-3.5	kHz
Quadrature phase error			1	°
Carrier suppression	25			dBc

Bit rate		100		kbps
Bit rate error			+/-90	ppm
Symbol rate		50		ksps
Output power - conducted (50 Ω)	150		250	mW
Output Power - radiated (EIRP)	70		100	mW
Spurious Emissions to meet ETSI 300-220		-54		dBm EIRP
Channel bandwidth		180	200	kHz
Start up time on to frequency		2	5	mS
Transmit enable time to full output power after start up time		100	200	uS
Current consumption at 5V - peak			100	mA

A3.6 Response Path Node Receiver

A number of methods exist to demodulate MSK, the simplest and most flexible is to convert the received signal down to a low IF frequency and then pass this into a DSP processor through a fast flash analogue to digital converter

All characteristics are over the full temperature range , -25 to +60°C, unless otherwise noted.

Characteristic	*Min*	*Typical.*	*Max*	*Unit*
Receive centre frequency		184.000		MHz
Carrier frequency error		0	+/-1.5	kHz
Received Quadrature phase errors	1		5	°
Bit rate		100		kbps

Bit rate error			+/-100	ppm
Symbol rate		50		ksps
Sensitivity for 14.5db SNR			-105	dBm
Image and other spurious responses	70			dB
Channel bandwidth @ -10db		180	200	kHz
Rejection at +/- 200KHz	60			dB
Carrier lock time			500	uS
Bit lock time			80	uS
Current consumption at 12V			500	mA

A3.7 Minimum Shift Keying MSK

MSK has four phases, so is able to transmit two bits together giving rise to its theoretical spectral efficiency of 2 bits/second/Hz. The four phase are defined as $\pi/4$ (45°), $3\pi/4$ (135°), $5\pi/4$ (225°) and $7\pi/4$ (315°).

In order to ensure that adjacent phase states only differ by one bit a Gray code is used to map the dibits to the 4 phases.

DIBIT	PHASE
11	45°
01	135°
10	225°
00	315°

A3.8 Layer 2- Data Link Layer

This section describes the structure of the data packet that is sent to and received from the physical layer which comprises the radio transmitters and receivers.

An additional complication of the data link layer protocol is the special collision avoidance strategies required, to allow the reading of a large number of meters simultaneously. This collision avoidance method is described in section 4.

A3.9 Standard Data Packet

Each packet sent either to a meter or received from a meter by a node is 320bits or 40 bytes long. It comprises 5 parts, the preamble, the start marker, the address section, the data payload and finally the 24bit CRC.

In general all words are sent most significant bit of the most significant byte first.

3 bytes	1 byte	9 bytes	24 bytes	3 bytes
PREAMBLE	START	ADDRESS	DATA PAYLOAD	CRC
0x555555	0x7e	……	…….	…….

A3.10 Preamble

The preamble is required to achieve bit lock on the incoming data and is defined as 24bits of reversals, that last bit of the preamble which occurs before the first bit of the start must be a logic 1. This ensures a 1 to 0 transition at the beginning of the start marker.

A3.11 Start Byte

This byte follows the preamble and provides a marker for byte synchronisation. It is normally defined as 126d or 0x7e. This byte is included in the CRC calculation.

A3.12 Address and Control Field

This contains source and destination address, the type field that describes the function of the message, an address mask byte, the 4 byte address, a sequence number, the data payload and a 24 bit CRC.

Address and control field:-

1 byte	1 byte	4 bytes	1 byte	1byte
TYPE	MASK	ADDRESS	SEQUENCE No	SPARE

Describes the function of the packet

24 bit address

Number of this packet in a long sequence

Address mask

7	6	5	4	3	2	1	0	Bits/ Function
x	x	x	x	0	0	0	0	All reply
x	x	x	x	0	0	0	1	Group A3
x	x	x	x	0	0	1	x	Group A3, A2
x	x	x	x	0	1	x	x	Group A3, A2, A1
x	x	x	x	1	x	x	x	Selective address
0	0	x	x	x	x	x	x	No collision avoidance (CA)
0	1	x	x	x	x	x	x	Vectored CA
1	0	x	x	x	x	x	x	Random CA
1	1	x	x	x	x	x	x	Programmed CA

TBF

x means don't care

A3.13 Data Payload

This area is unformatted and the 24 bytes can be used in for any purpose as they are neither modified nor interpreted at the data link layer.

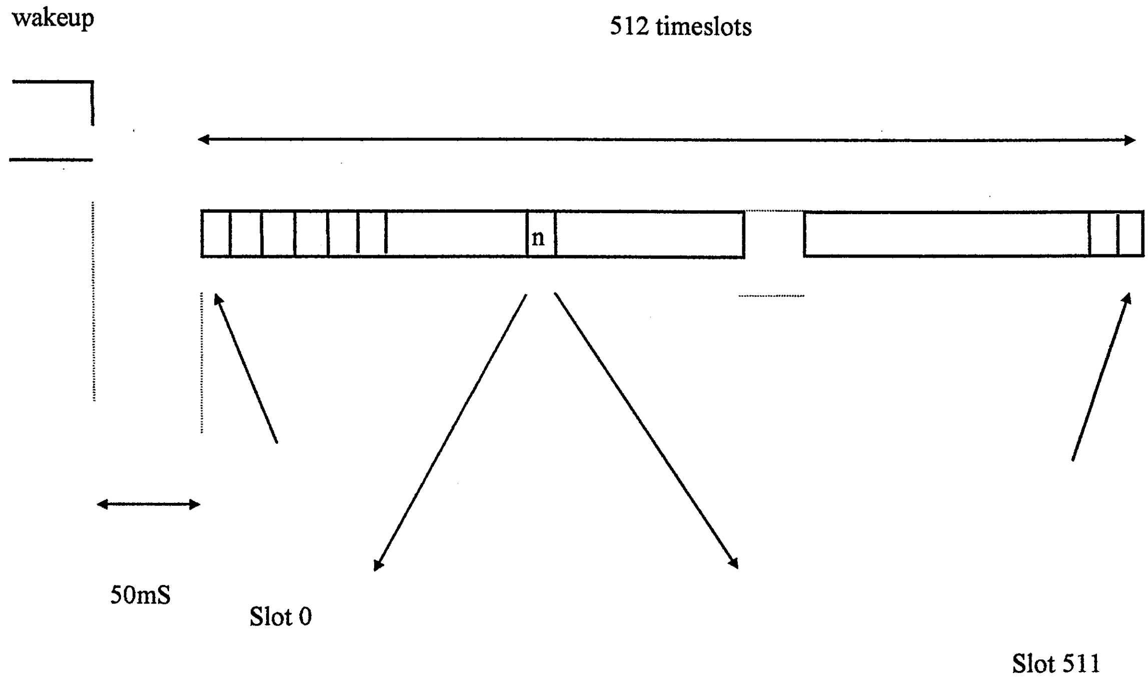
A3.14 Cyclic Redundancy Check

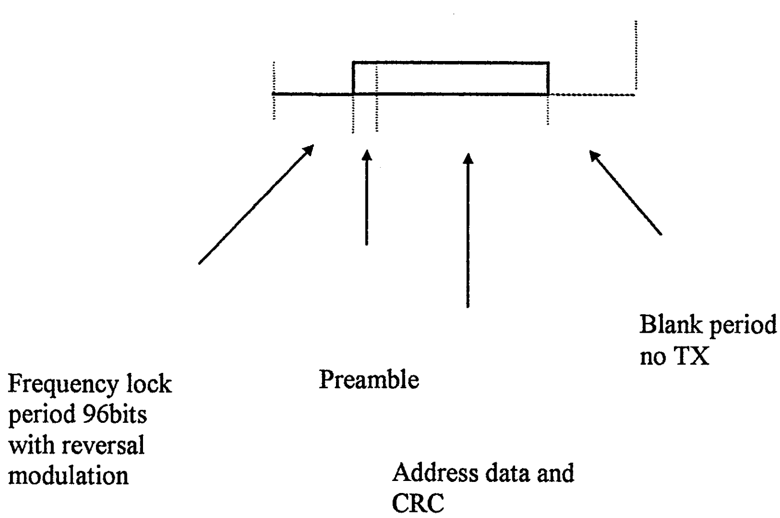
These 3 bytes are for validating the accuracy of the full packet. The calculation of the CRC begins from the first byte including the start, and the resultant CRC is the remainder after the data has been divided by the polynomial:-

$$X_{24} + X19 + X_{16} + X_{12} + X_5 + X_0$$

A3.15 Collision Avoidance Strategy

The main mode of operation of this AMR scheme is to make a "global" interrogate of all the meters in that Node's particular cell and then read the "simultaneous" replies with a modified TDMA technique. This technique involves allocating a time slot to each meter to prevent them transmitting simultaneously and so corrupting their data. The timeslots are 5.12mS wide and the first slot starts 50mS after the end of the wakeup signal. This delay is to allow the node and meter to switch from transmit to receive and vice versa. The allocation of the time slot calls for a software or 'soft' identity to be allocated to the particular meter at the time of installation of that particular meter transponder. A separate transmission protocol was triggered in the transponder by application of a magnet to a hidden reed relay during installation. The sequence then was the Node would receive the installation request and allocate the next available soft ID and timeslot to that transponder.





The actual timeslot in which a given transponder will transmit is determined in a number of ways which are selected by the most significant two bits of the MASK byte in the address field.

A3.16 Vectored

This mode uses the 9 Lsbits of the address field in the data packet sent in the wakeup message.

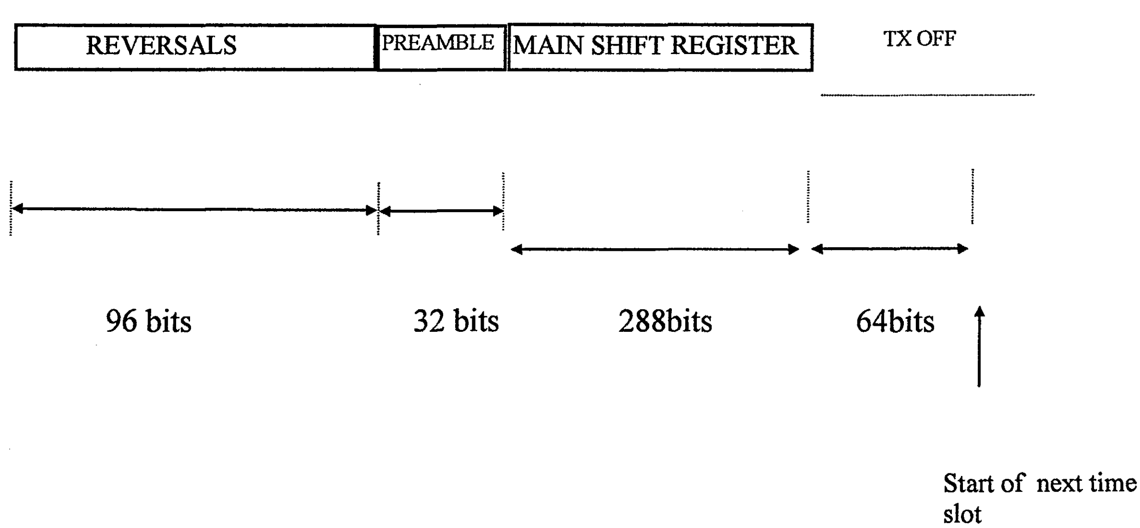
A3.17 Random

The slot is set to a random value. This value will be generated by a long pn code random number generator.

A3.18 Programmed

This will be the normal mode and the 9 bit number will come from a register loaded into the meter microcontroller during installation and is called the CA register.

Each transmission, both the wakeup and response, will be 512 bits long e.g. 512mS or 5.12mS respectively. The first 96 bits of the TX will be reversals (this is needed to achieve frequency lock in the DSP demodulator) followed by the preamble comprising; 3 bytes of reversals and the start byte (0x7e). The RF transmitter must be turned off for the balance of 64 bits which is to allow for timing errors before the next slot.



APPENDIX 4 Yorkshire Electricity Group PLC Transponder and Node design

This appendix describes the design of the Technology and Customer Trial transponders and details my responsibilities during the design phase and during the trials at Lindley and Goole. Both Technology and Customer trial systems consisted of one or more Node Transceivers that 'wake' the transponders up, or transmit a global request for a meter reading from all transponders allocated to that Node, and the transponders that are fitted onto the customers Siemens S2A electricity meters, see figure 43 page 111. These transponders respond to the Node wake up signal with a meter reading; transmitted by the transponder during its allocated time slot.

Technology Trial

The Technology Trial transponder design consisted of a narrow band single frequency superhetrodyne receiver used to 'wake' the transponder up plus a transmitter whose frequency generation was by numerically controlled oscillator. The interface to the electricity meter and control of the radio circuits was handled by an 8031 processor. This configuration was chosen to give the most flexible design in the time scales provided by the contract with Yorkshire Electricity Group PLC.

A numerically controlled oscillator (NCO) may be programmed to generate various types of frequency and phase modulated signals and in this case we used GMSK modulation with a 100kbit / second data rate. The control information for the NCO came from the 8031 processor. The receiver was designed around a Motorola FM receive IC similar to that used in the Customer trial detailed below. The on chip local oscillator was not used but an external crystal controlled Colpitts oscillator was designed with a 7^{th} overtone parallel resonance crystal running at 173.3MHz. The IF was chosen to be 10.7MHz so that cheap ceramic filters could be used to provide IF filtering while allowing an IF frequency sufficiently out of band to provide the receiver with adequate image performance (>30dB at 184MHz – 21.4MHz).

The Transmitter signal was generated in the NCO and then filtered using a 10.7MHz ceramic filter. The filtered 10.7MHz was amplified and then up-converted in a Gilbert cell active mixer; the 173.3MHz local oscillator for this up conversion was also used as the receiver local oscillator. The resulting signal was filtered to selected the 184MHz product and this was amplified in the power amplifier to give a transmit output power of 100mW, the transmit output filter was designed to reduce the harmonic content of the transmit signal as well as any residual mixing components at 10.7MHz, 173.3MHz and others. The output filter was also designed to have an insertion loss of less than 3 dB and to match the PA output impedance of approximately 9 ohms to the antenna impedance of 50 ohms.

The Node transceiver for the technology trial consisted of the Technology Trial transponder design mounted into a different box with serial RS232 connections from the 8031 processor (running different program code) to a PC that was used to collect the meter readings and all other statistics during the trial. The Node was mounted in a school room at the Yorkshire electricity Group PLC site at Lindley in West Yorkshire.

The radio design was laid out on a PCB similar in size to that used in the customer trial transponder and was fitted into the same module that fitted over a Siemens S2A electricity meter, see figure 47 page 116. The external antenna was connected via a BNC plug to the RF transmit receive switch.

My responsibility during the design phase was to design the RF circuits of the transponder from the output of the NCO to the antenna and the entire receiver up to the input to the 8031 processor. I was also responsible for the construction of the Node transceiver and was involved in interpreting the information gathered during the Technology trail phase.

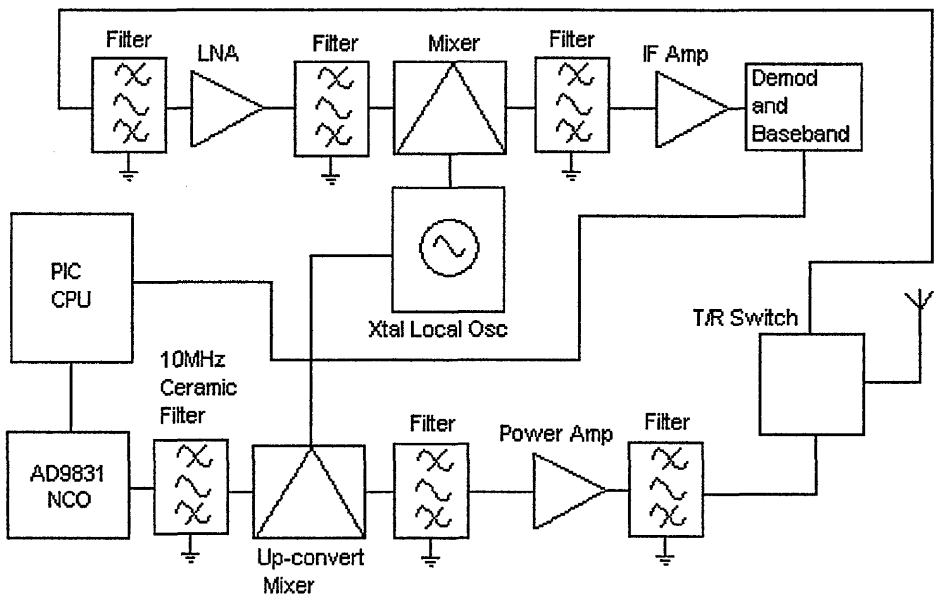


Figure A4-1 Block Diagram of Technology Transponder

Customer Trial

While the Technology trial was a limited trial with production of approximately 100 transponders and one simple Node, the Customer trial was to require 6 Nodes in operation that were largely unattended for the six month trial period plus the manufacture and installation of up to 2,500 transponders in customer premises at Goole in West Yorkshire. My responsibilities during this phase of the contract were to act as team leader for both Transponder and Node with special emphasis on the RF sections and as designer of the transmit power amplifiers and output stages for the Customer trial equipment both in the Transponder and the Node; I was also responsible for the manufacturing phase of the transponder production and I designed the automatic test equipment (ATE) used at the subcontract PCB manufacture site as well as writing the ATE software in HP VEE. During the trial I made many trips to Leeds and Goole to check on the operation of the equipment and to meet the representatives of Yorkshire Electricity Group PLC for updates and to give presentations of the progress and findings. I was also tasked with the analysis of the RF parts of the customer trial and with writing that section of the report to Yorkshire electricity Group PLC.

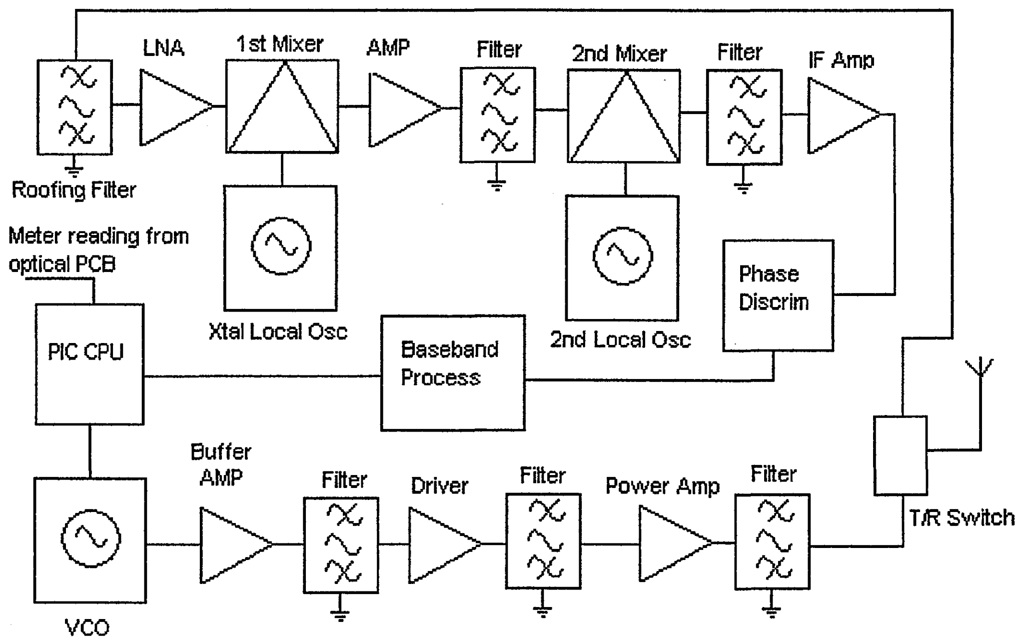


Figure A4-2 Block Diagram of YEG Customer Trial Transponder

A block diagram of the Yorkshire Electricity Group PLC Customer Trial is shown in Figure A4-2. The configuration is similar to that used in the Technology trial but changes were made in light of the experiences gathered during the Technology Trial and to facilitate cost savings in manufacture of 2,500 transponders. An internal antenna for the customer transponders was deemed essential by Yorkshire Electricity Group PLC to reduce the chances of customers damaging the transponders in some way. To that end I worked with the Technical Director of RAMAR Technology Ltd to produce a cheap internal antenna with adequate performance, see figure 48 page 117.

The receiver became a dual superhetrodyne design with the same first IF of 10.7MHz but with a second IF of 455 kHz which allowed better selectivity due to the narrow bandwidth

455 kHz ceramic filters used. The transmit stage was changed so that the GMSK signal was generated directly at 184MHz doing away with the expensive NCO and up-converting mixer. The 8031 processor was replaced by the PIC17C44 processor for reduced cost and ease of programming during the manufacturing phase and subsequently during the trial if required. The transmit/receive switch was implemented with two pin diode switches controlled in antiphase by the PIC17C44 processor

The radio PCB was designed to fit into carrier module of the S2A electricity meter as with the Technology Trial, see figure 48 page 117. The main processing power was supplied by a PIC17C44 microprocessor with 16kbytes of internal program memory, 454 bytes of ram. There was a further 1 k byte of EEPROM organised as 128 by 8 bytes addressed via the I^2C bus. This EEPROM was used to store the soft ID as well as up to 2 ½ days of half hourly meter records. That was addition to the 7 days worth of readings that may be stored in the Siemens S2AS electricity meters.

The receiver was a double conversion superhetrodyne design based around a Motorola MC3363DW. The first IF was at 10.7MHz with the second IF at 455kHz, this enabled the use of commercial ceramic filters giving good filter response and selectivity with low insertion loss and low cost. The LNA was implemented as a discrete component stage using a mosfet transistor chosen for low noise and high intermodulation performance. The first local oscillator at 173.3MHz was a crystal oscillator utilising a simple Colpitts circuit and this was connected to the 1st mixer (part of the MC3363W). The output at 10.7MHz was filtered in the 10.7MHz ceramic filter and fed into the IF amplifier, part of the MC3363W. After amplification the received signal was mixed with the second local oscillator, part of the MC3363W with an external crystal at 10.245MHz. The 2nd IF output at 10.7MHz was further amplified in the MC3363W and a Received signal Strength Indicator (RSSI) measurement made. This received signal strength indication was fed back into the PIC17C44 and then transmitted back to the Node as part of the trial. The received signal at 455 kHz was then demodulated in the phase discriminator and base band processor and the resulting digital signal was fed to the ADC converter in the PIC17C44 processor.

The Customer Trial transmitter was again a GMSK design but this time it was implemented using op amps and discrete transistors driven by the PIC17C44. The transmit oscillator was a modified Colpitts crystal oscillator as shown in Figure A4-3. The Crystal at 61.3333MHz was pulled by a varactor diode to vary its frequency. The varactor diode was driven by the PIC17C44 via some filtering and conditioning. This filtering and conditioning was used to set the drive level and voltage for the varactor diode as well as filtering out the higher frequencies in the base band data signal. The oscillator signal was tripled in the collector tank circuit of the oscillator and fed via a buffer stage and filter to a tuned amplifier used as a driver stage. The transmit signal was again filtered before being amplified in the power amplifier stage. The output filter was designed to reduce the 2nd and 3rd harmonics (368MHz and 552MHz), these being the most troublesome when meeting the MPT1601 specification, while not attenuating the transmit signal too much (2-3dB). The antenna board was connected to both transmit and receive circuits via two metal PCB standoff pillars and the transmit/receive switch.

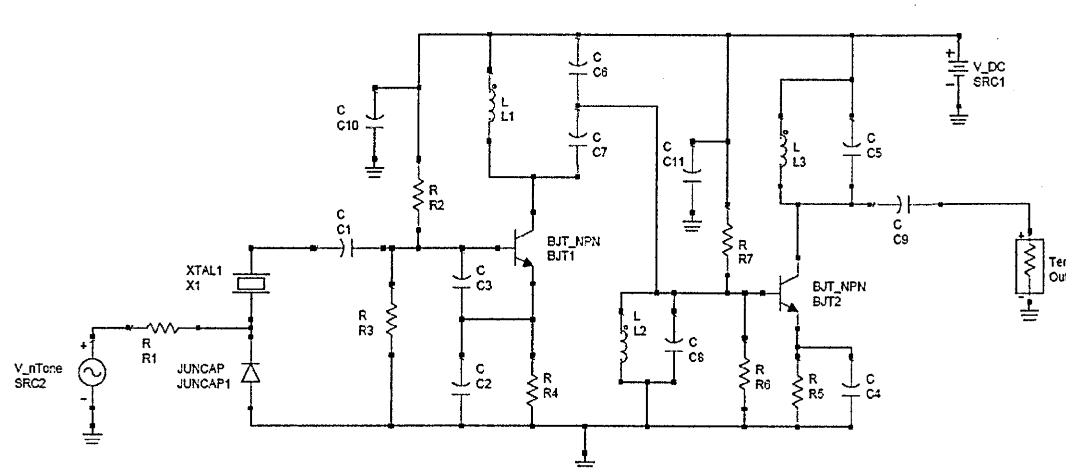


Figure A4-3 Circuit diagram of Transmit oscillator (Customer Transponder)

Also on the RF PCB was a reed switch used to trigger the PIC17C44 into a setup mode to log onto the Node, this reed switch was ignored once the Transponder had been configured and logged with its Node. Reactivation of the reed switch was only possible by reprogramming the transponder at the factory. This feature stopped the transponder logging onto more than one Node. Also on the RF board was a small LED visible from outside of the transponder enclosure and this flashed when the transponder had been interrogated by its Node. This LED was used during the development phase to show transponder activation and during the Customer Trial it gave the trials participants comfort that the Transponders were working.

The Node transmitter and receiver were again similar in design to the Customer transponder except advantage was taken to spread the radio circuits out and use three chamber helical filters at the receiver input and transmitter output. The insertion loss in the filters being compensated for by the high gain monopole or Yagi antennas used during the trial. Note that effectively two receivers where fitted in each node to allow for antenna diversity but this facility was not used during the Customer trial at Goole.

APPENDIX 5 STMicroelectronics Power Line Transceiver

The ST Microelectronics data sheet [17] gives the following characteristics for the ST7538P Power Line FSK Transceiver.

1. HALF DUPLEX FREQUENCY SHIFT KEYING (FSK) TRANSCEIVER
2. INTEGRATED POWER LINE DRIVER WITH PROGRAMMABLE VOLTAGE AND CURRENT CONTROL
3. PROGRAMMABLE INTERFACE can be SYNCHRONOUS or ASYNCHRONOUS
4. SINGLE SUPPLY VOLTAGE (FROM 7.5 UP TO 12.5V) with VERY LOW POWER CONSUMPTION (Iq=5mA)
5. INTEGRATED 5V VOLTAGE REGULATOR with (UP TO 100mA) WITH SHORT CIRCUIT
6. PROTECTION
7. 8 PROGRAMMABLE TRANSMISSION FREQUENCIES
8. PROGRAMMABLE BAUD RATE UP TO 4800BPS
9. RECEIVING SENSITIVITY 1 mV rms
10. SUITABLE TO APPLICATION IN ACCORDANCE WITH EN 50065 CENELEC SPECIFICATIONS
11. CARRIER OR PREAMBLE DETECTION BAND IN USE DETECTION
12. PROGRAMMABLE REGISTER WITH SECURITY CHECKSUM
13. MAINS ZERO CROSSING DETECTION AND SYNCHRONIZATION

This functionality makes the ST7538P PLC Transceiver an ideal candidate for use in the power-line transmission and reception in a PLC enabled electricity meter (to facilitate meter reading) or indeed in a public alarm system as described in Chapter 3 of this thesis. Both systems require a low data rate, robust, narrow bandwidth system that will transmit the required information reliably over the last kilometer between the customer premises and the electricity sub-station.

The ST7538P uses a Frequency Shift Keying (FSK) modulation scheme for both transmit and receive where two tones are used, one to represent a 1 in the data and the other tone to represent a 0. These two tones pull the carrier away from it's centre frequency and the ST7538P allows selection of 8 different centre frequencies, which may be used for example to avoid blocked channels due to some form of interference.

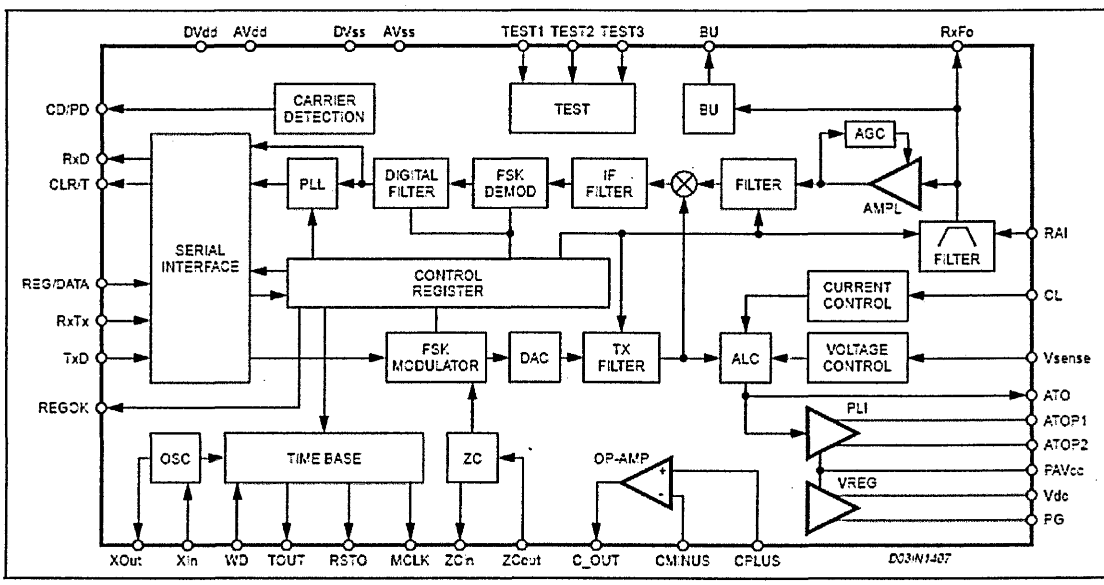


Figure A5.1 Block Diagram of the ST7538P internal functions [17]

The ST7538P also has functionality built in to interface directly between a microcontroller and the mains supply and the ST7538P includes the power line drivers to inject the PLC signals onto the mains. These power line drivers are programmable for both voltage and current output and have built in feed back mechanisms (shown as voltage control and current control blocks in Figure A5.1) thus ensuring the PLC output conforms to EN50065.

The receive section of the ST7538P power line transceiver incorporates a carrier detection circuit as well as filtering and an FSK demodulator plus a phase lock loop (PLL) clock recovery circuit; this receiver system is sensitive to PLC signals on the mains as small as 1mV rms. The received signals are stored in a register for the microcontroller to read.

ST Microelectronics supply the ST7538P Power Line Transceiver in a power line modem demo kit that is detailed in the application note AN1714 ST7538 FSK POWER-LINE TRANSCEIVER DEMO-KIT DESCRIPTION [16]. A photograph of the ST Microelectronics power line transceiver demo board is shown in figure A5.2 and two of these demo boards where used during the trails of the public alarm system as described in Chapter 3 of this thesis.

The circuit of the ST7538P and associated parts is given in Figure A5.3 and the circuit references in Chapter 3 refer to this circuit diagram. C11 is shown as a 33nF capacitor and this was changed in some Nimbus units as well as the ST Microelectronics demo boards to 68nF to reduce the signal loss between the mains wiring and the ST7538P. This increase in capacitance will tighten the coupling between the mains wiring and the input / output filter circuits and cause some broadening of the filter response allowing more noise into the receiver and more signal onto the mains in transmit mode. This increase in transmit signal is still within the limits laid down in EN50065. A similar effect may be achieved by leaving C11 as 33nF and reducing the value of L4 and this was tried during the trials at the Kepier trial site. Note that reducing the inductance of a fixed size inductor has the effect of reducing the series impedance and dc resistance and thus increasing the loaded Q (quality factor) of the inductor and of the filter circuit. This in turn should increase the selectivity of the filter circuit.

The potentiometer referred to in Chapter 3 of this thesis is a control that sets the voltage feedback level into the ST7538P voltage control function of the ST7538P and when adjusted during the trials this could be used to set the peak to peak voltage output of the

ST7538P for local conditions; this control is usually not touched except during fault finding conditions.

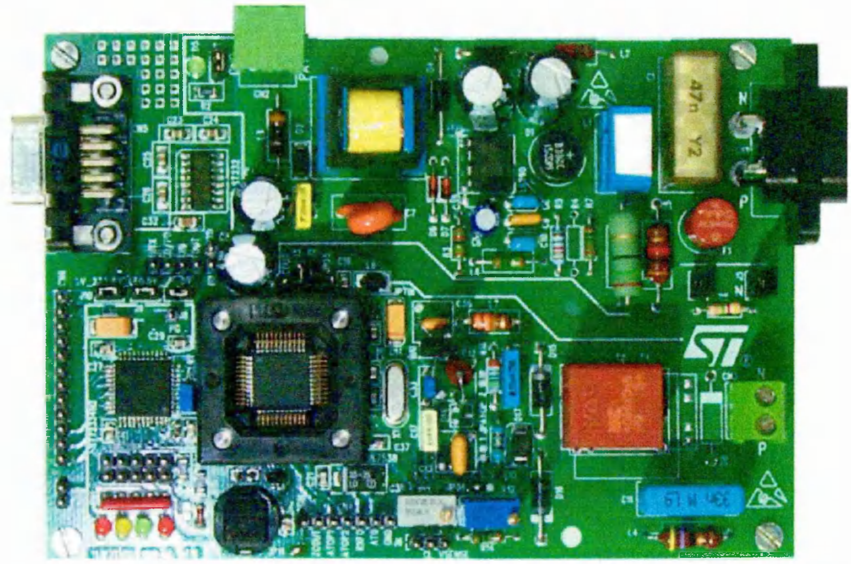


Figure A5.2 ST Microelectronics Power Line Transceiver Demo Board [16]